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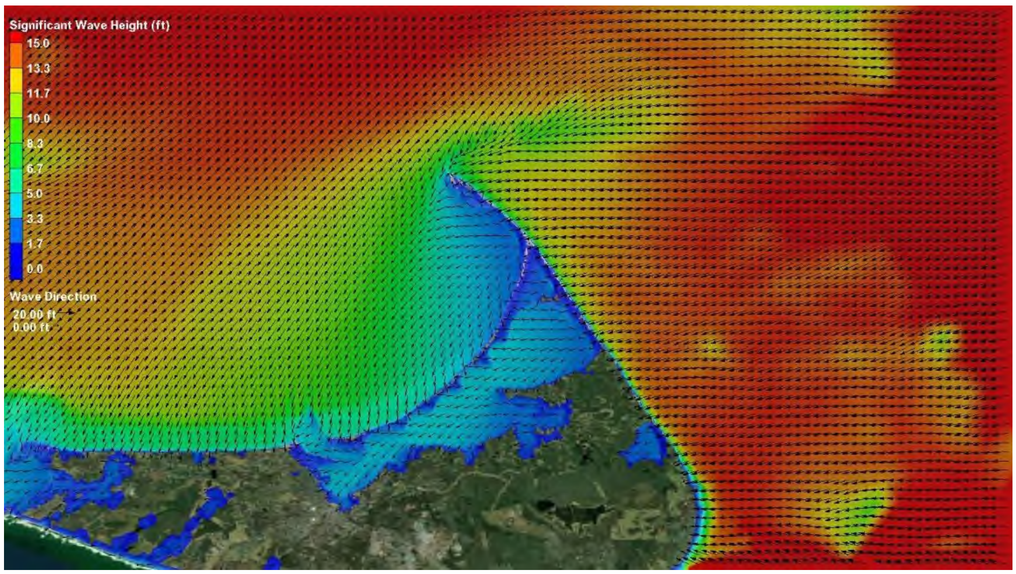
Coastal Engineering Study
Proposed Town Pier Improvements
Nantucket Harbor, Nantucket, MA



PREPARED FOR:

Town of Nantucket
16 Broad Street
Nantucket, MA

Date: February, 2019
File No. 18.0174001.01

GZA GeoEnvironmental, Inc.
144 Elm Street | Amesbury, MA, 01913
781-278-4800

31 Offices Nationwide
www.gza.com

TABLE OF CONTENTS

EXECUTIVE SUMMARY

GZA performed this coastal engineering study in support of the design of the proposed Town Pier Improvement Project including: 1) currently planned improvements to the floating dock, including float replacement and dredging; and 2) potential future improvements to the existing wave fence and/or installation of an additional wave attenuator. The purpose of GZA's study is to provide the Town with a comprehensive and defensible, risk-based project design basis and associated environmental loads for the floating dock replacement project. Environmental loads include those due to the combined effects of wind, water levels and waves and are characterized for different annual exceedance probabilities (presented as recurrence intervals in years).

Numerical wave modeling analysis was performed by GZA to probabilistically characterize key environmental design parameters. GZA utilized the metocean data as input to numerical wave modeling to simulate both existing conditions and expected conditions (i.e., sea level rise) over the design service life (50 years, year 2070).

The results of the study were used to recommend the environmental conditions for design of the proposed replacement of the floating dock. Recommendations for two design conditions:

1. An <u>operational condition</u>, which assumes that the docks are fully-occupied with vessels during a moderate coastal flood event (on the order of a 50-year to 100-year recurrence interval coastal flood event); and
2. A <u>survivability condition</u> which evaluates vacated docks during an extreme storm event (on the order of a 100-year recurrence interval coastal flood event assuming Category 1 to 2 hurricane intensity winds).

The operational condition design basis (i.e., 50 to 100-year recurrence interval events[1]) include intense extratropical nor'easters. The results are presented in **Tables 5** and **6**, and are generally consistent with the conditions assumed for GZA's 2015 floating pier replacement guide pile calculations (Reference "Nantucket Town Floats, Nantucket, MA, Proposed Concrete Float Pile Design", GZA Project 18.0172082.00, April 2015).

Additional findings of this study are also relevant to long range planning related to the Town Pier, and include but are not limited to:

1. GZA's numerical model can be useful for future evaluation of structure improvements and design optimization, including predicting the effects and performance benefits of proposed modifications.
2. The existing Town Pier is vulnerable to coastal flood events. This vulnerability will significantly increase over time due primarily to the effects of sea level rise. Sea level rise will increase the frequency of damaging storm events. Specifically, with a fixed deck elevation of +/- 6 feet, damaging event risk is on the order of 5 to 10-year recurrence intervals. During the design service (next 50 years), the probability of damaging events will be on the order of annually. Increasing the elevation of the fixed deck will need to be considered in future plans.
3. The existing Town Pier wave fence provides some wave attenuation benefit, but its effectiveness is limited due to its limited length and wave shadow. A significant increase in length would be required to be effective. The effectiveness of the existing wave fence is also limited due to its elevation (wave protection level) which is currently overtopped during storm events. Future modifications to the wave fence should include an increase in height as well as length. Additional limitations are presented in the text of this report.
4. Other future alternatives, including a floating wave attenuator, may be a more effective approach to wave attenuation while providing additional benefits such as additional berthing capacity. This would need further evaluation and design.
5. Based on limited modeling performed as part of this study, the proposed modifications and expansion to the Nantucket Boat Basin under consideration do not appear to have a negative effect (and may have a net positive effect) on the Town Pier.

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[1] The water level and wave conditions presented for the operational condition are generally consistent with the 100-year recurrence interval event. A range of recurrence intervals have been presented to characterize probability due to uncertainty about the hurricane contribution to wind and wave risk.

INTRODUCTION

GZA performed this coastal engineering study in support of the design of the proposed Town Pier Improvement Project including: 1) currently planned improvements to the floating dock, including float replacement and dredging; and 2) potential future improvements to the existing wave fence and/or installation of an additional wave attenuator. The purpose of GZA's study is to provide the Town with a defensible, risk-based project design basis and associated environmental loads for the floating dock replacement project. Environmental loads include those due to the combined effects of wind, water levels and waves and are characterized for different annual exceedance probabilities (presented as recurrence intervals in years).

The study includes a detailed analysis of available metocean data (wind, waves and water levels) to statistically characterize the observed environmental conditions and develop input to design wave characteristics applicable to the Town Pier. The study also performed numerical wave modeling using the SWAN (Simulating WAves Nearshore) model. The benefits of using numerical wave modeling were: 1) to more accurately simulate the complex harbor geometry and bathymetry; and 2) model the effects of existing and proposed structures on wave transformation in the vicinity of the Town Pier (specifically, the effects due to the Town Pier wave fence and the adjacent Nantucket Boat Basin wave fence.

In addition to modeling existing conditions, the study also modeled the effects of additional structure improvements/modifications currently under consideration. These include: 1) extension of the Nantucket Boat Basin wave fence; 2) extension of the Town Pier wave fence; and 3) the combined effects of each of these. Another improvement under consideration by the Town is the installation of a separate wave attenuator (floating dock) to further attenuate wave height in the vicinity of the Town Pier. The wave characteristics (wave height, period and transformation) developed by the study were used to inform what wave attenuator characteristics would be required (i.e., length, location, orientation) to effectively reduce wave heights in the vicinity of the Town Pier.

This report, including attachments, presents the results of the study. Recommendations are presented for two design conditions: 1) an operational condition, which assumes that the docks are fully-occupied with vessels during a moderate coastal flood event (on the order of 50-year to 100-year recurrence interval); and 2) a survivability condition which evaluates vacated docks during an extreme storm event (on the order of 100-year recurrence interval coastal flood event assuming Category 1 to 2 hurricane intensity winds).

We also note that the information presented in the Coastal Engineering Study, while focused on this project, will be useful for harbor planning and for future coastal resilience and climate adaptation planning for the island.

This study is subject to the attached Limitations (**Attachment 9**).

BACKGROUND

The Town fixed pier and floating dock at Nantucket, MA provide berthing for small craft private and commercial fishing vessels. **Figures 1** and **2** show the location of the Town Pier in relation to Nantucket Harbor and nearby structures. **Figure 3** shows the bathymetry in the vicinity of the Town Pier (in feet relative to NAVD88).

The floating dock supports vessels on the order on 20 to 40 feet in length, with additional dinghy dock space. The existing timber system consists of an approximately 12-foot by 48-foot access float with four timber piles (two per side), an approximately 8-foot by 427-foot main float with 8 steel piles (14-inch diameter, spaced at about 50 feet to 57 feet on center), 12 finger floats ranging in length from 20 feet to 30 feet with timber piles at the end of each finger. **Attachment 2** presents existing pier details.

The Town intends to replace the existing timber float system with a concrete float system that has a similar configuration and layout as the existing system. The work associated with the proposed concrete floating dock system involves the following: 1) removing the existing timber access float, floating dock, finger piers and guide piles; 2) installing new concrete floats; 3) installing 20 new 16-inch diameter steel pipe piles along the north side of the float system; and 3) installing 10 new 12-inch diameter steel pipe guide piles at the end of the finger floats.

In 2015, GZA completed design calculations for the proposed floating dock guide piles (Reference "Nantucket Town Floats, Nantucket, MA, Proposed Concrete Float Pile Design", GZA Project 18.0172082.00, April 2015). GZA also completed project plans and specifications (Reference "Nantucket Town Pier Float Replacement and Dredging Project" Sheets 1 through 5, June, 2018).

The Town Pier Float Replacement and Dredging Project was publicly bid in June 2018. Based on the bid results that were received by the Town, schedule logistics including; time-of-year work restrictions, float manufacture lead times, and slip-holder agreements and the Town's request to consider some design related changes, the project was postponed and not awarded.

This Coastal Modeling Report provides the environmental design basis for the Town Pier Floats and associated guide piles, in support of GZA's 2015 design calculations for the guide piles and specifications for the concrete floats. The design of the new concrete floats and hardware will be the responsibility of the dock vendor. The proposed improvements design service life is conservatively assumed to be 50 years (assumed end of service life at year 2070[2].

STUDY SCOPE OF WORK

The coastal engineering study included the following tasks:

1. **Metocean Data Analysis.** GZA compiled and analyzed relevant metocean data analysis to establish: 1) directional wind speeds; 2) tidal and extreme (i.e., storm surge) water levels; and 3) deep water wave heights and wave periods associated with a range of annual exceedance probabilities, applicable to the project site.

    a) Tidal Datums. The tidal datums were developed for the current tidal epoch based on the NOAA Station 8449130 Nantucket Island tide station, located at the Steamship Authority dock in Nantucket Harbor. The tide station was established in October 1963 and installed at its current location in 1990. (See **Attachment 1**.)

    b) Historical Storm Study. An evaluation of historical coastal storms impacting Nantucket was performed to identify the storm types and characteristics expected to contribute to the Town Pier facility failure risk (up to the 100-year recurrence interval; 1% annual exceedance probability). The evaluation was also performed to interpret and validate GZA's statistical analysis of wind speed and water level. The storm types contributing to the pier failure risk include: 1) extratropical nor'easters; and 2) tropical cyclones (tropical storms and hurricanes). (See **Attachment 3**.)

    c) Wind Analysis. GZA developed design "all direction" and "directional" wind speed frequency curves for the 3-second gust and 1-minute sustained wind speeds at 10 meters above ground. The curves were developed using Generalized Extreme Value (GEV) statistical analysis of data from Nantucket Airport. Design wind speeds were also developed based on ASCE 7-10 guidance for 3-second gusts at 10 meters, Exposure C. Prevailing (i.e., typical) annual wind conditions were also analyzed based on data measured at the NOAA Nantucket meteorological land station. (See **Attachment 4**.)

[2] The design service life is the assumed period for which a structure or part of it is to be used for its intended purpose with anticipated maintenance but without major repair being necessary. The longevity of marine-grade concrete and epoxy coated steel structures in marine environments is typically in the range of 40 to 50 years. Typically, more exposed portions of a structures, such as members exposed to the direct elements or in the intertidal zone, need replacement or repairs more frequently than the 40 to 50-year duration.

d) Water Level Analysis. GZA developed stillwater-frequency curves based on several data sources including: 1) GZA's GEV statistical analysis of the NOAA Station 8449130 Nantucket Island tide station water level data; 2) save point data results from the US Army Corps of Engineers (USACE) North Atlantic Coast Comprehensive Study (NACCS); and 3) stillwater-frequency data presented in the effective FEMA Flood Insurance Study for transects in the project vicinity. GZA developed Relative Sea Level Rise values for the project design life based on NOAA 2017 sea level rise projections and approximate projection probabilities and using the USACE sea level rise calculator for the NOAA Nantucket Tide Station. GZA developed synthetic storm hydrographs to characterize peak water level durations. (See **Attachment 5**.)

2. **Wave Modeling.** Utilizing input from the metocean data analysis, GZA performed a numerical wave analysis using the SWAN (Simulating WAves Nearshore) model to evaluate waves generated by wind and deep-water waves propagating toward the site (from the USACE Wave Information Studies [WIS] stations and USACE NACCS save point data) for a range of different probabilities including the 1-year, 2-year, 5-year, 10-year, 25-year, 50-year, 100-year. SWAN is a third-generation wave model developed by the Delft University of Technology. SWAN calculates random, short-crested wind-generated waves in coastal regions and inland waters. The model results present wave vectors. The simulated wave heights presented here represent significant wave heights, H_s and breaking wave heights, H_b (where depth limited wave conditions exist).

GZA-developed local wind field for model boundary condition input. Wave model simulation wind intensities were selected to reflect conservative, directional wind statistics. The simulations were performed for those wind directions known to specifically impact the Town Pier.

GZA's SWAN model, with variable resolution, encompasses all of Nantucket, with a high and very high-resolution model mesh within the Nantucket Harbor/Head of the Harbor and the immediate project area, respectively. The purpose of this approach was to ensure that the model captured the wave transformation effects of the adjacent Nantucket Boat Basin's seaward piers on waves encroaching on the Town pier and docks. GZA's model also simulated the effects of a hypothetical shoreline breach (north end of Head of the Harbor) on waves propagating within the Nantucket Harbor/Head of the Harbor toward the Town pier and the effects of extending the existing wave fence.

The wave modeling included the following. (See **Attachment 5**.)

a) Model Mesh Development. GZA developed a Digital Elevation Model using 2016 NOAA NGS Lidar.

b) Model Simulations. GZA performed a total of 28 wave simulations representing a range of different recurrence interval wind speeds and water levels, including:

- Wind direction sensitivity analyses;
- Ocean wave harbor attenuation sensitivity;
- Design simulations:
  - Current conditions, multiple recurrence intervals;
  - Sea level rise conditions;
  - Barrier beach breach simulation;
  - Simulation of structure improvements/modifications under consideration, including:
    - Extension of the Nantucket Boat Basin wave fence;
    - Extension of the Town Pier wave fence (several iterations); and
    - A combination of each of these.

3. **Probability Analysis.** A probability analysis was performed to develop risk-informed design basis recommendations (i.e., the appropriate recurrence interval assumed for design loads, in consideration of the structure performance during the design service life). The probabilistic characterization of water levels, waves and wave crest elevations is presented in **Attachment 8**.

RESULTS

Detailed results are presented in the report **Attachments**. Simulated wave heights are summarized on the **Tables 1** through **6** in **Attachment 6**. The results of the metocean data analysis and wave simulations indicate the following general findings:

1. Ocean Wave Attenuation. The entrance to Nantucket Harbor is protected by breakwaters located on both sides of the harbor channel. The jetties at the harbor entrance significantly attenuate ocean waves within the harbor. Therefore, waves affecting the Town Pier are local, wind-generated waves within the harbor. The fetch within the harbor is fairly long at 3.8 miles and is in a northeast-southwest direction. Waves generated within the harbor, over this fetch, are partially attenuated over the shallow areas in the harbor and due to interaction with shoreline features such as First Point, Second Point and Third Point.

2. Storm Characteristics. Storm types that create extreme winds, water levels and waves in the harbor include both: 1) extratropical nor'easters; and 2) tropical cyclones, including tropical storms and hurricanes. The available water level data (NOAA Nantucket tide station) and wind data (Nantucket Airport) indicate that, for the duration of the available data records, all of the observed, elevated wind and water level events at Nantucket contributing to structure risk have been due to extratropical storms. These storms can be long in duration, lasting multiple tide cycles. They also result in a dominant wind direction (from the north to east) that aligns with the harbor fetch and is conducive to wave development within Nantucket Harbor. However, nor'easters are typically limited in intensity and typically have peak wind speeds (3-second gust and sustained winds) less than hurricanes. While not evident in the available Nantucket tide station water level and Nantucket Airport wind data, tropical cyclones occur relatively frequently in the vicinity of Nantucket. Since the 1850's, a total of 87 tropical cyclones (including tropical storms and hurricanes) have passed within a 100-mile radius of Nantucket. About 30 of these were hurricanes including about 19 Category 1 hurricanes, 7 Category 2 Hurricanes and 4 Category 3 (major) hurricanes. The approximate hurricane recurrence interval in the vicinity of Nantucket is about 13 to 16 years. The approximate recurrence interval of major hurricanes in the vicinity of Nantucket is about 58 to 62 years. The probability of a hurricane track that would result in intense north to east winds over Nantucket is expected to be very low. Effectively, this would be a storm with a northeast track, passing to the southeast of the island and within about 20 to 50 miles of the island. **Attachment 3** present several historic hurricanes (since the 1850s) that met these general criteria but occurred outside of the available Nantucket wind and water level record.

3. Wind Direction and Intensity. GZA performed a frequency analysis of wind speed and directionality. The hourly 1-minute sustained wind speed data at the Nantucket Memorial Airport, located near the project site at Longitude: -70.061°, Latitude: 41.253°, was downloaded from the National Climatic Data Center (NCDC) and analyzed using GEV statistics. The period of record covers 1948 to present. The maximum wind speeds (1-minute sustained wind speed) relative to different directional quadrants are presented in **Attachment 4**. The largest magnitude wind speeds are predicted from the south quadrant (135° to 225° in degrees clockwise from north). The predicted 100-year mean recurrence interval 1-minute sustained wind velocity at 10 meters from the south is about 80 mph.[3] The predicted 100-year mean recurrence interval, 1-minute sustained wind speed at 10 meters elevation and aligned with the harbor fetch is between 60 and 70 mph. As discussed previously, the maximum winds in the observed wind data at Nantucket Airport are all associated with nor'easters. In comparison, the ASCE/SEI 7-10

[3] Note that high southerly winds within the record include short duration events (likely thunderstorms).

specified wind speed (3-second gust) for the project area is 120 mph for the 100-year recurrence interval. This value is converted to a 1-minute sustained wind speed at 10 meters height of approximately 98 mph. The ASCE/SEI wind speeds for the 100-year recurrence interval are consistent with hurricanes (a low level Category 2 hurricane). Prevailing (i.e., typical) 2-minute sustained winds, averaged by month are less than 15 knots (+/- 17 mph), with monthly mean values less than 10 knots (+/-12 mph).

4. Extreme Water Levels. Stillwater flood-frequency curves were developed for Nantucket Harbor (1-year through 500-year recurrence intervals) utilizing three data sources, including: the NOAA Nantucket tide station; 2) the USACE North Atlantic Coast Comprehensive Study (NAACS); and 3) the effective FEMA Flood Insurance Study (FIS). The stillwater flood-frequency curves and data are presented in **Attachment 5**. In general, the three data sources result in similar mean flood-frequency predictions at the Town Pier. Two of the sources (FEMA and the GZA Nantucket Tide Station analysis) were developed based on statistical interpretation of historic wind (Nantucket Airport) and water level data over a limited time period. The USACE NACCS data was developed based on statistical interpolation of numerical simulations of historic extratropical storm tracks and synthetic tropical cyclone storm tracks. The mean 100-year recurrence interval stillwater elevation is 5.8 feet NAVD88. Climate change will result in increasing sea levels over the life of the facility. Relative sea level rise projections have been developed for the NOAA Nantucket tide station (NOAA Technical Report NOS CO-OPS 083, January 2017). The NOAA 2017 Intermediate sea level rise projection at Nantucket has an associated global sea level rise projection with non-exceedance probabilities of approximately 2% to 17% by the year 2100 and is reasonably conservative projection for use in pier design. The projected NOAA 2017 Intermediate sea level change (relative to current) is about 2 feet. The relative sea level rise values can be linearly-superimposed to the predicted current tides and flood-frequency curves. The projected 100-year recurrence interval stillwater elevation is Elevation 8.1 feet NAVD88. The Town Pier structure is located seaward of mean low water and wave set-up along the structure is not expected to be significant. A wave set-up of 0.5-foot is assumed resulting in a Total Water Level (i.e.., stillwater plus wave set-up) of 6.3 feet NAVD88 (current) and 8.6 feet NAVD88 (year 2070).

5. Wave Model Simulations. The numerical wave simulations evaluated: 1) the fetch-limited wave heights within Nantucket Harbor; and 2) the effects of the existing structures (the Town Pier wave fence and the adjacent boat basin wave fence). A sensitivity analysis to evaluate the effects of the jetties on waves within Nantucket Harbor indicates that the jetties significantly attenuate ocean waves. The results indicate that ocean waves are nearly completely attenuated within the vicinity of the Town Pier and that waves that occur at the Town Pier are due principally to local wind fetch within Nantucket Harbor. A sensitivity analysis was also performed to evaluate the wind direction resulting in the largest waves within the harbor, in the vicinity of the Town Pier. Wind from the northeast (about 45^o to 50^o clockwise from north) corresponds to the longest fetch within the harbor and resulted in the largest waves. Wave simulation results are presented in **Attachment 6**.

   a) Current Conditions: Wave simulations were performed for multiple recurrence interval conditions and for local winds speeds (based on both statistical analysis of Nantucket Airport) and ASCE/SEI 7-10. Simulations using wind speeds based on ASCE/SEI 7-10 results are shown in **Attachment 6, Table 2**. Simulations using wind speeds based on GZA's analysis of Nantucket Airport are shown in **Attachment 6, Table 5.** Wave heights along the Town Pier are reduced (relative to wave heights within the harbor) by the presence of the Town Pier wave fence. Significant wave heights (H_s) range from:

      a. about 1 to 1.5 feet (1-year recurrence interval);

      b. 2 to 2.5 feet (10-year recurrence interval);

      c. 2.5 to 3 feet (50-year recurrence interval); and

      d. 2.5 to 3.2 feet (100-year recurrence interval).

b) Sea Level Rise: Design simulations were also performed to evaluate the effect of sea level rise on wave height at the Town Pier. Wave heights at the project site increased minimally due to sea level rise (approximately 0.2 – 0.4 foot).

c) Barrier Beach Breach: Barrier beach overtopping is expected to occur during low probability extreme flood events. A barrier beach breach is unlikely considering the beach width and elevation. Regardless, a simulation was performed to evaluate a hypothetical 800-foot wide breach to a depth of Mean Low Water (Elevation -1.84 feet, NAVD88) at the northeast barrier beach directly across from the Town Pier (see **Attachment 6** Run 13B). The simulated wave heights at the Town Pier are the same as those without the breach indicating minimal effect on wave height at the Town Pier due to a breach.

d) Wave Periods and Wavelengths: Typical of short fetch wind-generated waves, wave periods are small (around 3 to 4 seconds). Corresponding wave lengths in the vicinity of the Town Pier are on the order of 20 to 30 feet. The modeled wave periods are generally on the order of the natural period of small vessels.

The numerical model simulations, in conjunction with physical site observation, characterize the expected, representative wave characteristics at the Town Pier, including the effects of the existing wave fences. **Figures 4** through **9** present wave vectors that are representative of a northeast wind (with about 70 mph, 1-minute sustained winds) and maximum stillwater elevation of 6 feet NAVD88. **Figure 6** indicates attenuated, but complex wave conditions within the harbor inlet. At the peak stillwater of Elevation 6 feet NAVD88, the jetties are inundated. **Figures 4** and **5** demonstrate indicate the significant refraction and attenuation of ocean waves along the ocean and Sound shores and at the harbor entrance. These figures show wave refraction at Great Point and along Coatue Beach. These figures also show that intermittent areas along the barrier beaches are overtopped at the peak stillwater of Elevation 6 feet NAVD88.

Waves within the harbor are not influenced by ocean waves and are aligned with the northeast wind direction. **Figures 7** through **9** show the wave transformation effects of the Town Pier wave fence and the adjacent Nantucket Boat Basin wave fence. One effect of these structures is to create a reflected wave that radiates outward from the structures creating an irregular wave field (highlighted by red areas on the figures). A second effect is for these structures to cause localized wave refraction, in particular within the area between the Town Pier and the adjacent Boat Basin to the north of the Town Pier. Based on the numerical wave model results, wave refraction along with shoaling effects appear to create an area of elevated wave heights directed toward the mid-section of the Town Pier. This modeled condition is generally consistent with long term observations by the Town. The white lines presented on these figures represent the zone of increased wave heights due to these structure effects as observed by the Town and are shown for comparison to the model output. **Figure 10** is similar, but represents a more intense wind speed (ASCE 7-10 100-year recurrence interval wind speed of 98 mph). **Table 1** summarizes the modeled wave heights at the Town Pier.

Recurrence Interval (years)	Significant Wave Heights (Hs) at SWAN Model Output Save Points at Town Pier (in feet)			
	2	3	4	5
Prevailing Monthly Wind Speed	0.7	0.7	0.8	0.7
1	1.1	1.2	1.3	1.1
2	1.6	1.8	1.9	1.6
5	1.8	2.0	2.2	1.8

Recurrence Interval (years)	Significant Wave Heights (Hs) at SWAN Model Output Save Points at Town Pier (in feet)			
10	1.9 to 2.0	2.2 to 2.3	2.3 to 2.4	2.0 to 2.1
25	2.1 to 2.4	2.3 to 2.8	2.4 to 2.8	2.1 to 2.5
50	2.2 to 2.6	2.4 to 3.0	2.5 to 3.0	2.2 to 2.7
100	2.2 to 2.7	2.5 to 3.2	2.7 to 3.2	2.3 to 2.8

Table 1: Summary of Modeled Significant Wave Heights (Hs) at the Town Pier (Model output save points 2 through 5)

The elevation of the Town Pier fixed pier deck is +/- 6 feet NAVD88 which is about the predicted 100-year recurrence interval stillwater elevation. The elevation of the Town Pier wave fence is +/- 4 feet NAVD88. A limitation of the numerical wave numerical model is that the wave fence is modeled as a "barrier feature", which extends vertically without limit. In reality: 1) wave breaking at the wave fence will result in overtopping of the deck; and 2) wave crest elevations of unbroken waves (which are higher than the deck elevation) will inundate the deck. Although unconfirmed by our analysis, it is likely that the air gap between the top of the wave fence and the fixed deck results in impulsive wave forces (acting as uplift on the bottom of the deck) also occurs. Wave crest elevations are presented in **Attachment 8**. The current 100-year recurrence interval stillwater flood elevation is +/- 6 feet NAVD88, about the same elevation as the fixed deck. Lower probability storms will result in submergence of the deck. With sea level rise, the frequency of events that result on submergence of the deck will increase.

The model simulations were also compared to Town Pier damage observed during the January 27, 2015 nor'easter, a historic winter storm. GZA completed a post-storm inspection and documented the damage (report date February 2015). Storm characteristics are presented in **Attachment 3**. The January 27, 2015 storm had a peak stillwater elevation at Nantucket of 4.9 feet NAVD88. The estimated sustained (1-minute, 10-meter at the nearby NOAA land station) peak wind was +/- 50 mph from the northeast. Based on wind intensity, the estimated wind recurrence interval was about 2 years (all direction wind curve) and about 10-years (north to east direction wind curves). Based on the observed water levels, the storm was consistent with a 10-year recurrence interval water level event. Overall, the event was generally consistent with a 10-year recurrence interval wind/water event. For a similar recurrence interval event, GZA's numerical wave model simulations results indicated significant wave heights (H_s) of +/- 2.5 feet. One observed damage benchmark was the lifting of the float above the pile (third pile landward from the east; top of pile at +/- Elevation 9.1 feet NAVD88). For a 2 to 3-hour peak storm condition (near peak wind and water level) and assumed 3.5 second wave period, we have estimated that about 2,000 to 3,000 waves impacted the pier coincident with elevated water levels during the storm. Assuming that at least a few waves (of the 2,000 to 3,000 waves) occurred during that time with wave crest elevations at or above Elevation 9.1 feet (top of pile, resulting in lifting of the float), assuming a wave crest elevation at 0.7 x wave height above stillwater, and back calculating the significant (H_s) wave height (note - H_{1000} = +/-2 x H_s), the estimated peak significant wave height during the January 2015 storm in the lifted pier was +/-2.9 feet (on the order of 2.5 to 3.0 feet), which is generally consistent with the model simulations.

6. <u>Existing Wave Fence Performance.</u> The existing Town Pier wave fence attenuates wave heights during storms, but the extent of wave attenuation is limited along the length of the fixed pier and floating piers due to the limited length of the existing wave fence. As indicated on **Figures 9** and **10**, significant wave shadowing (wave heights reduced to +/- 1 foot) is limited to a zone extending about 80 to 100 feet landward of the existing wave fence. Wave refraction occurs at both the north end and south end of the wave fence. Due to the limited length of the wave fence, refracted waves may combine to form larger waves along sections of the piers located immediately landward of the shadow zone. GZA performed one simulation (see **Attachment 6, Table 2 Runs 13D**) to

evaluate wave heights without the wave fence (for comparison). The results indicate that during this simulated event (100-year recurrence interval event with ASCE/SEI 7-10 wind speeds), on average the wave fence reduces the wave height along the pier length by about 20% relative to a condition with no wave fence (ranging from 12% to 28%). Based on the model results, the greater wave attenuation (+/- 30%) due to the existing wave fence was predicted close to the fence (model output save point 2) and southwest (i.e., directly downwind) of the wave fence (model output save point 5). About 80% to near 100% wave height attenuation occurs immediately behind the fence (blue area on **Figure 10**). The presence of the wave fence also causes wave reflection seaward of the fence. During the modeled event, the wave fence increased the wave height in front (seaward) of the wave fence by about 20% due to wave reflection, relative to the condition without the wave fence.

In terms of berthing tranquility, ASCE Manual 50, 3rd Edition "Planning and Design Guidelines for Small Craft Harbors" presents guidance for tolerable agitation heights (see **Attachment 7**). For wave periods in the 2 to 6 second range and the 1-year and 50-year recurrence interval wave/water level events, desirable wave heights are shown below:

Recurrence Interval	**Wave Climate**	**Head Sea**	**Beam Sea**
1	Excellent	<0.75-foot	<0.4 foot
	Good	<1 foot	<0.5 foot
	Moderate	<1.25 feet	<0.6 foot
50	Excellent	<1.5 feet	<0.6 foot
	Good	<2 feet	<0.75 foot
	Moderate	<2.5 feet	<1 foot

Table 2: Small Craft Harbor Tolerable Wave Height Guidance for 2 to 6 second Period Waves

In general, waves within a marina/small craft harbor basis should be 1-foot or less and ideally lower for beam seas for operational conditions and about 2 feet or less for structure damage minimization of floating docks.

Based on observation and the numerical wave modeling results, these criteria are generally met during the prevailing wind conditions and are generally exceeded for most of the pier length (except the shadow area immediately behind the wave fence) during storm events (e.g., 1-year and 50-year recurrence interval events).

7. Structure Improvement/Modification Simulations. Based on information provided by the Town, we understand that improvements/modifications to the existing wave fence at the Nantucket Boat Basin are being considered (see **Figure 15**). Extension of the existing Town Pier wave fence is also under consideration. Installation of a separate wave attenuator located seaward of the Town Pier is also under consideration. The intent of the Town Pier improvements/modifications is to reduce the wave height along the Town Pier for the purposes of: 1) creating an improved operational wave climate consistent with small vessel harbor guidance (**Table 2**); 2) reduce on-going damage and repair/replacement costs of the fixed and floating piers; and/or 3) potentially reduce the size and cost of the proposed replacement floating pier components.

   GZA performed several additional wave model simulations to preliminarily evaluate the effects of the structure improvements/modifications currently under consideration. The simulations considered an extreme storm (100-year recurrence interval event with ASCE/SEI 7-10 wind speeds) to maximize the simulated effects. The purpose of these simulations was not to optimize a final design, but rather to assess the overall effects of modifying the structures in order to inform future planning and design.

Alternative	Significant Wave Heights (Hs) at SWAN Model Output Save Points at Town Pier (in feet)			
	2 (northeast)	3 (northwest)	4 (southeast)	5 (southwest)
Condition with No Town Pier Wave Fence	3.7	3.6	4	3.8
Existing Condition (**Figure 10**)	2.7	3.2	3.2	2.8
% wave height reduction relative to no wave fence	27%	11%	20%	26%
Alternative extending Town Pier Wave Fence to the north and south (**Figure 12**)	2.0	2.9	2.7	2.5
% wave height reduction relative to existing condition	26%	10%	16%	11%
Alternative further extending Town Pier Wave Fence to the north (**Figure 14**)	1.1	2.3	-	-
% wave height reduction relative to existing condition	59%	28%	-	-
Alternative extending Nantucket Boat Basin Wave Fence with no change to the Town Pier (**Figure 16**)	2.4	2.9	3.1	2.7
% wave height reduction relative to existing condition	11%	9%	3%	4%
Alternative extending Nantucket Boat Basin Wave Fence and extending Town Pier Wave Fence to the north (**Figure 17**)	0.9	2.4	3.1	2.8
% wave height reduction relative to existing condition	67%	25%	3%	0%

Table 3: Summary of Modeled Significant Wave Heights (Hs) at the Town Pier (model output save points 2 through 5). Comparative analysis of structure improvement/modification alternatives.

Figure 11 shows an alternative of extending the Town Pier wave fence at each end (about 45 feet to the north and 65 feet to the south). **Figure 12** shows the model simulation results for this alternative. **Figure 13** shows an alternative of further extending the Town Pier wave fence at the north end (about 100 feet to the north). **Figure 14** shows the model simulation results for this alternative. **Figure 15** (provided by the Town) shows: 1) an alternative extending the Nantucket Boat Basin wave fence to the east; and 2) in conjunction, also extending the Town Pier wave fence at the north end (about 75 feet to the north). **Figure 16** shows the model simulation results for extending the Nantucket Boat Basin wave fence, with not change to the existing Town Pier wave fence. **Figure 17** shows the model simulation results for extending the Nantucket Boat Basin wave fence, with also extending the existing Town Pier wave fence to the north. **Attachment 6** presents the simulation results details. **Table 3** summarizes the results at the 4 model output save points.

Although limited in scope, the results presented in **Table 3** indicate the following preliminary findings:

1. The numerical wave model, with some limitation, appears to be effective in simulating the effects of structure changes on wave transformation.
2. As noted previously, the presence of the existing Town Pier wave fence reduces the wave heights along the Town Pier relative to a condition with no wave fence (on the order of 11% to 27%, location dependent).
3. Extending the Town Pier wave fence to the north further reduces wave heights along the northern portions of the Town Pier. However, as expected, the benefit is sensitive to the length of the extension.
4. Extending the Nantucket Boat Basin wave fence as shown on **Figure 15** appears to have a positive effect on wave height along the Town Pier.
5. Of the simulations performed, the combination of extending the Nantucket Boat Basin and the Town Pier wave fence provides the greatest wave height reduction.
6. To achieve the small craft tolerable wave height criteria presented in **Table 2**, about a 55% (1 year recurrence interval) to 70% (50-year recurrence interval) reduction in wave height relative to the existing condition would be required. Significantly larger modification of the existing wave fence would be required to achieve that criteria.

The implication of these results is that a major increase in the length of the wave fence would be required as well as a possible realignment of the existing wave fence to significantly reduce wave heights at the Town Pier relative to the existing condition. These modifications are complex due to: 1) wave interaction with the boat basin structures to the north; and 2) boat navigation considerations. Additional work, including additional simulations and cost analysis, would be required to further evaluate the benefits and limitations of other alignments/lengths.

8. <u>Wave Attenuator (Floating Breakwater).</u> An alternative to modification of the existing wave fence would be construction of a separate, floating wave attenuator (floating breakwater) located seaward of the existing Town Pier. A feasibility evaluation of this alternative is beyond the scope of this study and requires: 1) navigation/boat passage study; and 2) a cost analysis. In general, it would be desirable to locate the wave attenuator seaward of the existing Town Pier and adjacent Boat Basin wave fence to avoid interaction with reflecting waves during storms and to provide a navigation fairway. **Figure 18** presents a conceptual representation of a wave attenuator (floating concrete dock) alternative.

   Design of a floating wave attenuator is on a case-by-case basis. General criteria are presented below, excerpted from information provided by Marinetek:

   - Based on practical experience it is commonly accepted that the significant wave height in the marina basin should be less than 35 cm (1.1 feet). Trying to achieve this in all weather conditions is not economically sensible and therefore the following criteria are used when selecting the breakwater model:
   - *Maximum Operating Conditions:* The floating breakwater attenuates incident wave heights by about 55-75% relating to a constant wind velocity of 15 m/s[4]. That is approximately 30 knots or 6-7 Beaufort (35 mph).
   - *Storm Design Conditions:* The attenuation capacity decreases to a level of about 40-55% which relates to a constant wind velocity of 15 m/s to 23 m/s. That is 30-45 knots or 7-9 Beaufort (35 to 52 mph). The breakwater remains undamaged.
   - *Survival Conditions (Force Majeure):* These conditions with winds greater than 23 m/s (52 mph) would typically appear during a heavy storm that statistically occurs once in 50 years. The attenuation capacity

[4] Wind duration identified as 1 hour. Equivalent, 1-minute sustained wind speed values will be higher.

is less than 30% and minor structural damage may occur although the frame of the breakwater still holds out, provided that the sinkers and the chains are designed to stand these ultimate loads.

Table 4 presents preliminary estimates of attenuated wave heights relative to the modeled incident wave heights (model output save point 7). Note that the attenuated wave heights represent attenuation solely by the floating wave attenuator (i.e., between the wave attenuator and the Town Pier wave fence). Additional attenuation along the Town Pier would be provided by the existing wave fence.

Recurrence Interval (years)	Significant Wave Heights (Hs) at SWAN Model Output Save Points at Town Pier (in feet)			
	Incident Wave Save Point 7	Maximum Operating Condition	Storm Design Condition	Survival Condition
Prevailing Monthly Wind Speed	1.2	0.3 to 0.5	-	-
1	1.8	0.5 to 1	-	-
2	2.5	0.6 to 1.1	-	-
5	2.9	-	1.3 to 1.7	-
10	3.1 to 3.3	-	1.5 to 2	-
25	3.3 to 3.9	-	1.8 to 2.3	-
50	3.5 to 4.2	-	-	3
100	3.6 to 4.5	-	-	-

Table 4: Preliminary Estimates of Attenuated Wave Heights due to the Floating Wave Attenuator based on General Performance Criteria presented by Marinetek.

RECOMMENDATIONS

Recommendations are presented for environmental design conditions for the Nantucket Town Pier Float Replacement and Dredging Project. In the absence of building structures, the Town Pier design is not regulated under the State Building Code.[5] The ASCE Manual 50, 3rd Edition "Planning and Design Guidelines for Small Craft Harbors" provides applicable design guidance for this project. Consistent with this guidance document, the establishment of the appropriate design criteria is based on acceptable risk. Risk considerations include: 1) the cost of construction versus long term repair and maintenance costs; 2) tolerable operational use under different conditions; and 3) public safety. Risk evaluation requires: 1) defining the intensity of load or event that the pier must accommodate; 2) determining the likelihood of the event; and 3) estimating the chance that the event will occur within a given time period (i.e., the design service life of the Town Pier improvements). The environmental conditions that contribute to the pier live loads (i.e., wind, water levels and waves) are characterized in terms of their probability, specifically the annual exceedance probability. This equivalent probability is also characterized in terms of recurrence interval. For example, a 100-year recurrence interval event has a 1% chance of being met or exceeded in any given year.

The final decision as to the acceptable risk is, ultimately, that of the Project Owner. **Attachment 8** provides a probability analysis to better characterize the cumulative hazard probabilities.

[5] One possible exception to this assumption is if the pier is required to be operational for use as emergency response during coastal flood events.

The following presents GZA's design basis recommendations for two design conditions: 1) an operational condition, which assumes that the docks are fully-occupied with vessels during a moderate coastal flood event (on the order of a 50-year to 100-year recurrence interval coastal flood event); and 2) a survivability condition which evaluates vacated docks during an extreme storm event (on the order of a 100-year recurrence interval coastal flood event). The operational condition design basis (i.e., 50 to 100-year recurrence interval events[6]) include intense extratropical nor'easters.

<u>Operational Condition (approximately 50-year to 100-year recurrence interval event):</u>

- 1-minute sustained, wind speed: 68 mph from any direction
- 3-second gust: 82 mph from any direction
- Stillwater elevation (current condition): 5.8 feet NAVD88
- Total water level (stillwater with wave setup current condition): 6.3 feet NAVD88
- Stillwater elevation (year 2070, with 2.30 feet of sea level rise): 8.1 feet NAVD88
- Total water level (year 2070, stillwater with wave setup): 8.6 feet NAVD88
- Wave height:
    - Hs = 2.6 feet
    - Assuming Raleigh distribution
        - $H_{1/10}$ = 1.27 Hs = 3.3 feet
        - $H_{1/100}$ = 1.67 Hs = 4.3 feet
        - $H_{1/1000}$ (or H max) = 2 Hs = 5.2 feet
    - Wave period: 3.5 seconds
    - Wave length: 25 to 29 feet
- Maximum wave crest elevations (current conditions):
    - With Hs = 8.1 feet NAVD88
    - Assuming Raleigh distribution
        - $H_{1/10}$ = 8.6 feet NAVD88
        - $H_{1/100}$ = 9.3 feet NAVD88
        - $H_{1/1000}$ (or H max) = 10.0 feet NAVD88
- Maximum wave crest elevations (year 2070, with 2.30 feet sea level rise):
    - Hs = 10.4 feet NAVD88
    - Assuming Raleigh distribution
        - $H_{1/10}$ = 10.9 feet NAVD88
        - $H_{1/100}$ = 11.6 feet NAVD88
        - $H_{1/1000}$ (or H max) = 12.2 feet NAVD88
- Hydrograph: see **Attachment 5**
- Recommended freeboard: 2 feet
- Top of pile: El. 12.2 + 2 feet = 14.2 feet NAVD88 = 16.1 feet MLW

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[6] The water level and wave conditions presented for the operational condition are generally consistent with the 100-year recurrence interval event. A range of recurrence intervals have been presented to characterize probability due to uncertainty about the hurricane contribution to wind and wave risk.

Survivability Condition (approximately 100-year recurrence interval event, with conservative ASCE 7-10 wind speed):

- 1-minute sustained, wind speed: 98 mph from any direction
- 3-second gust: 120 mph from any direction
- Stillwater elevation (current condition): 5.8 feet NAVD88
- Total water level (stillwater with wave setup current condition): 6.3 feet NAVD88
- Stillwater elevation (year 2070, with 2.30 sea level rise): 8.1 feet NAVD88
- Total water level (year 2070, stillwater with wave setup): 8.6 feet NAVD88
- Wave height:
    - Hs = 3.2 feet
    - Assuming Raleigh distribution
        - $H_{1/10}$ = 1.27 Hs = 4.1 feet
        - $H_{1/100}$ = 1.67 Hs = 5.3 feet
        - $H_{1/1000}$ (or H max) = 2 Hs = 6.4 feet
    - Wave period: 4 seconds
- Maximum wave crest elevations (current conditions):
    - With Hs = 8.5 feet NAVD88
    - Assuming Raleigh distribution
        - $H_{1/10}$ = 9.1 feet NAVD88
        - $H_{1/100}$ = 10.0 feet NAVD88
        - $H_{1/1000}$ (or H max) = 10.8 feet NAVD88
- Maximum wave crest elevations (year 2070, with 2.30 sea level rise):
    - With Hs = 10.8 feet NAVD88
    - Assuming Raleigh distribution
        - $H_{1/10}$ = 11.5 feet NAVD88
        - $H_{1/100}$ = 12.3 feet NAVD88
        - $H_{1/1000}$ (or H max) = 13.1 feet NAVD88
- Hydrograph: see **Attachment 5**
- Recommended freeboard: 2 feet
- Top of pile: El. 13.1 + 2 feet = 15.3 feet NAVD88 = 17.1 feet MLW

The design conditions presented above are generally consistent with the conditions assumed for GZA's 2015 floating pier replacement guide pile calculations (Reference "Nantucket Town Floats, Nantucket, MA, Proposed Concrete Float Pile Design", GZA Project 18.0172082.00, April 2015). **Tables 5** and **6** present a comparison summary.

The design conditions recommended above for establishment of environmental live loads are conservatively estimated to be the conditions at the end of the 50-year service life (assumed year 2070).

LONG RANGE PLANNING CONSIDERATIONS

Certain findings of this study are relevant to long range planning related to the Town Pier:

1. GZA's numerical model can be useful for future evaluation of structure improvements and design optimization, including predicting the effects and performance benefits of proposed modifications.
2. The existing Town Pier is vulnerable to coastal flood events. This vulnerability will significantly increase over time due primarily to the effects of sea level rise. Sea level rise will increase the frequency of damaging storm events. Specifically, with a fixed deck elevation of +/- 6 feet, damaging event risk is on the order of 5 to 10-year recurrence intervals. During the design service (next 50 years), the probability of damaging events will be on the order of annually. Increasing the elevation of the fixed deck will need to be considered in future plans.
3. The existing Town Pier wave fence provides some wave attenuation benefit, but its effectiveness is limited due to its limited length and wave shadow. A significant increase in length would be required to be effective. The effectiveness of the existing wave fence is also limited due to its elevation (wave protection level) which is currently overtopped during storm events. Future modifications to the wave fence should include an increase in height as well as length. Additional limitations are presented in the text of this report.
4. Other future alternatives, including a floating wave attenuator, may be a more effective approach to wave attenuation while providing additional benefits such as additional berthing capacity. This would need further evaluation and design.
5. Based on limited modeling performed as part of this study, the proposed modifications and expansion to the Nantucket Boat Basin under consideration do not appear to have a negative effect (and may have a net positive effect) on the Town Pier.

ENVIRONMENTAL DESIGN CONDITION	Apr-15	Current Study
OPERATIONAL CONDITION		
Wind - 1 minute sustained	60 Knot (69 MPH) NE Direction	68 MPH any Direction
Wind - 3 second gust	n/a	82 MPH any Direction
Recurrence Interval	+/- 100-year	+/- 100-year
Water - Stillwater Elevation (current condition)	EL 6.1 NAVD88 (FEMA)	EL 5.8 NAVD88
Water - Total Water Level (stillwater with wave setup)	EL 8.8 NAVD88 (FEMA)	EL 6.1 NAVD88
Water - Stillwater Elevation (w/2.3 ft sea level rise yr. 2070)	n/a	EL 8.1 NAVD88
Water - Total Water Level (stillwater with wave setup and sea level rise yr. 2070)	n/a	EL 8.6 NAVD88
Wave Height (Hs)	2.5 feet	2.6 feet
Wave Height ($H_{1/10}$)	4.9 feet	3.3 feet
Wave Height ($H_{1/100}$)	6.4 feet	4.3 feet
Wave Height ($H_{1/1000}$)	n/a	5.2 feet
Wave Period	2.5 second	3.5 second
Wave Length		25 to 29 feet
Maximum Wave Crest Elevation Hs (Current Condition)	+/- 8 NAVD88	8.1 NAVD88
Maximum Wave Crest Elevation ($H_{1/10}$)	n/a	8.6 NAVD88
Maximum Wave Crest Elevation ($H_{1/100}$)	n/a	9.3 NAVD88
Maximum Wave Crest Elevation ($H_{1/1000}$)	n/a	10.0 NAVD88
Maximum Wave Crest Elevation Hs (year 2070 with Sea Level Rise)	n/a	10.4 NAVD88
Maximum Wave Crest Elevation ($H_{1/10}$)	n/a	10.9 NAVD88
Maximum Wave Crest Elevation ($H_{1/100}$)	n/a	11.6 NAVD88
Maximum Wave Crest Elevation ($H_{1/1000}$)	n/a	12.2 NAVD88
Recommended Pile Top Height (based on 2 ft freeboard)		14.2 NAVD88
Recommended Pile Top Height (based on 2 ft freeboard)	17.5 MLW	16.1 MLW

Table 5: Comparison of Recommended Operational Environmental Design Conditions to GZA 2015 Calculations (Reference "Nantucket Town Floats, Nantucket, MA, Proposed Concrete Float Pile Design", GZA Project 18.0172082.00, April 2015)

SURVIVABILITY CONDITION		
Wind - 1 minute sustained	60 Knot (69 MPH) NE Direction	98 MPH from any direction
Wind - 3 second gust	n/a	120 MPH from any direction
Recurrence Interval	+/- 100-year	+/- 100-year
Water - Stillwater Elevation (current condition)	EL 6.1 NAVD88 (FEMA)	EL 5.8 NAVD88
Water - Total Water Level (stillwater with wave setup)	EL 8.8 NAVD88 (FEMA)	EL 6.3 NAVD88
Water - Stillwater Elevation (w/2.3 feet sea level rise yr. 2070)	n/a	EL 8.1 NAVD88
Water - Total Water Level (stillwater with wave setup and sea level rise yr. 2070)	n/a	EL 8.6 NAVD88
Wave Height (Hs)	4.0 feet	3.2 feet
Wave Height ($H_{1/10}$)	4.9 feet	4.1 feet
Wave Height ($H_{1/100}$)	6.4 feet	5.3 feet
Wave Height ($H_{1/1000}$)	n/a	6.4 feet
Wave Period	3.8 second	4.0 second
Maximum Wave Crest Elevation Hs (Current Condition)	e	8.5 NAVD88
Maximum Wave Crest Elevation ($H_{1/10}$)	n/a	9.1 NAVD88
Maximum Wave Crest Elevation ($H_{1/100}$)	n/a	10.0 NAVD88
Maximum Wave Crest Elevation ($H_{1/1000}$)	n/a	10.8 NAVD88
Maximum Wave Crest Elevation Hs (year 2070 with Sea Level Rise)	n/a	10.8 NAVD88
Maximum Wave Crest Elevation ($H_{1/10}$)	n/a	11.5 NAVD88
Maximum Wave Crest Elevation ($H_{1/100}$)	n/a	12.3 NAVD88
Maximum Wave Crest Elevation ($H_{1/1000}$)	n/a	13.1 NAVD88
Recommended Pile Top Height (based on 2 ft freeboard)		15.3 NAVD88
Recommended Pile Top Height (based on 2 ft freeboard)	17.5 MLW	17.1 MLW

Table 6: Comparison of Recommended Survivability Environmental Design Conditions to GZA 2015 Calculations (Reference "Nantucket Town Floats, Nantucket, MA, Proposed Concrete Float Pile Design", GZA Project 18.0172082.00, April 2015)

Figures

Figure 1: Nantucket Harbor, Nantucket Island

Figure 2: Nantucket Harbor, Nantucket Island

Figure 3: Bathymetry in vicinity of Town Pier (feet, NAVD88). Source data: 2016 NOAA NGS (National Geodetic Survey) Topobathy Lidar DEM: Martha's Vineyard and Nantucket Island, MA (the horizontal resolution is 3 feet).

Figures 4 through 9: Typical Wave Characteristics during event with 70 mph 1-minute sustained northeast wind and Elevation 6 feet NAVD88 Stillwater Elevation

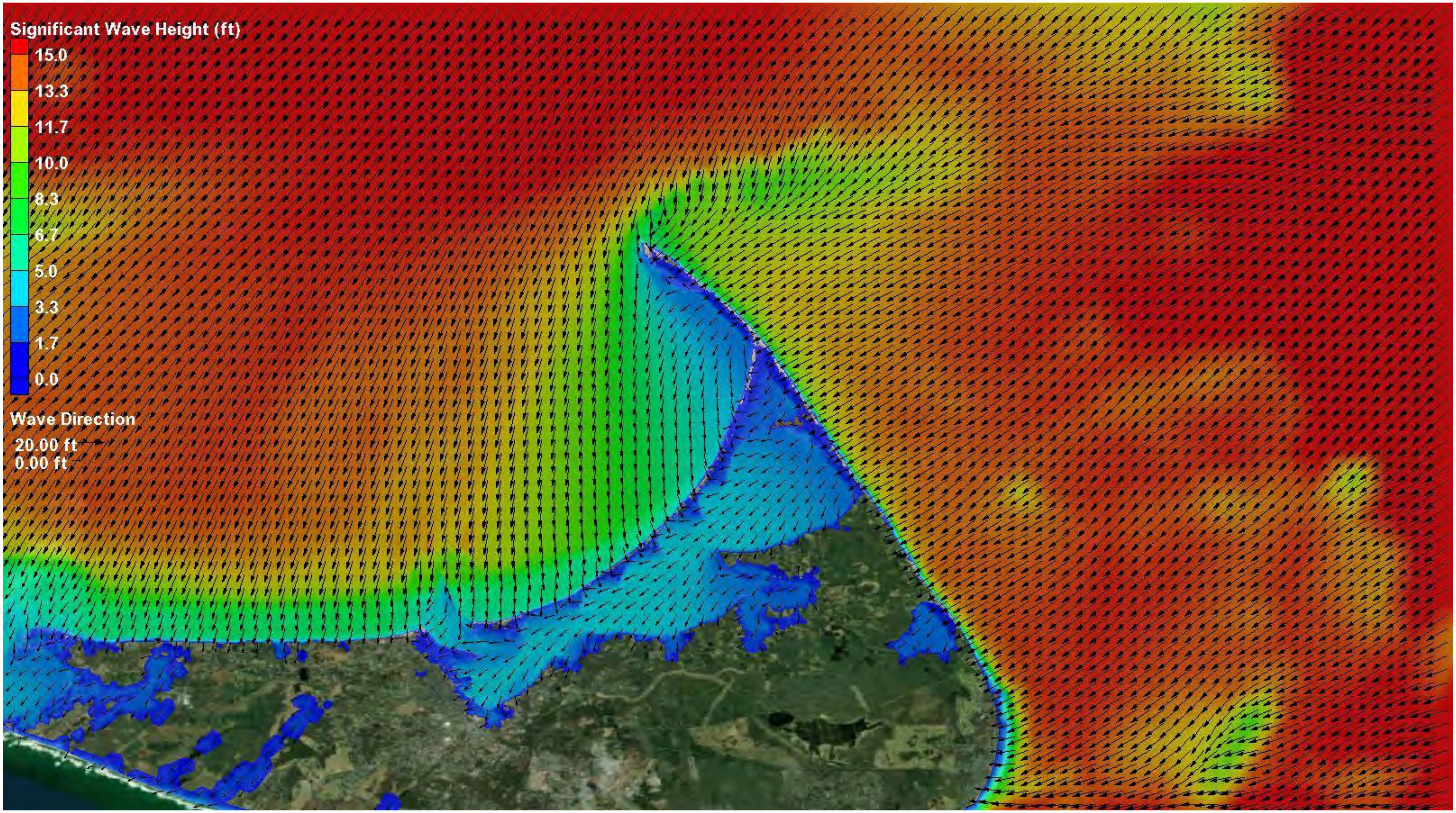


Figure 4

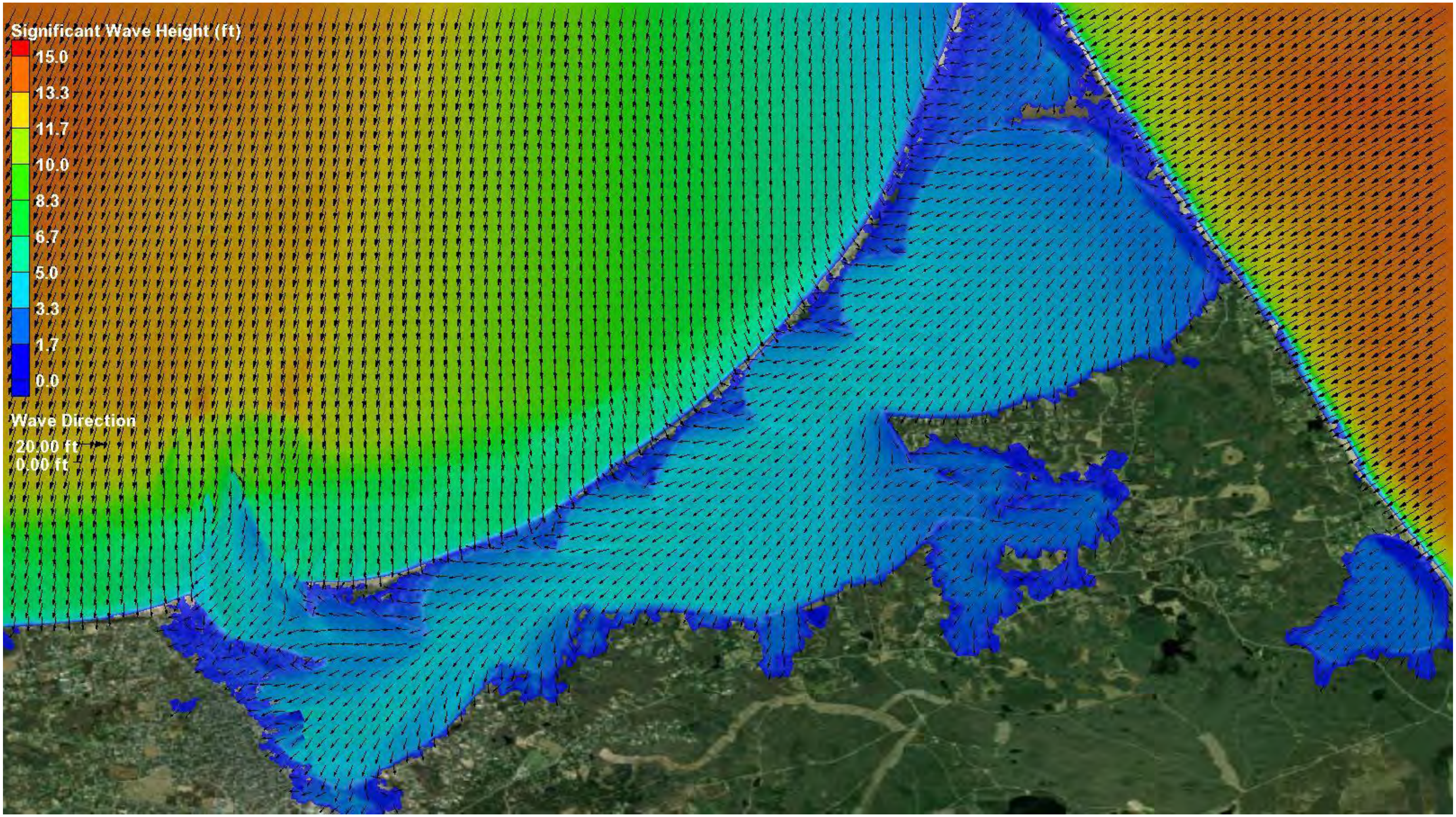
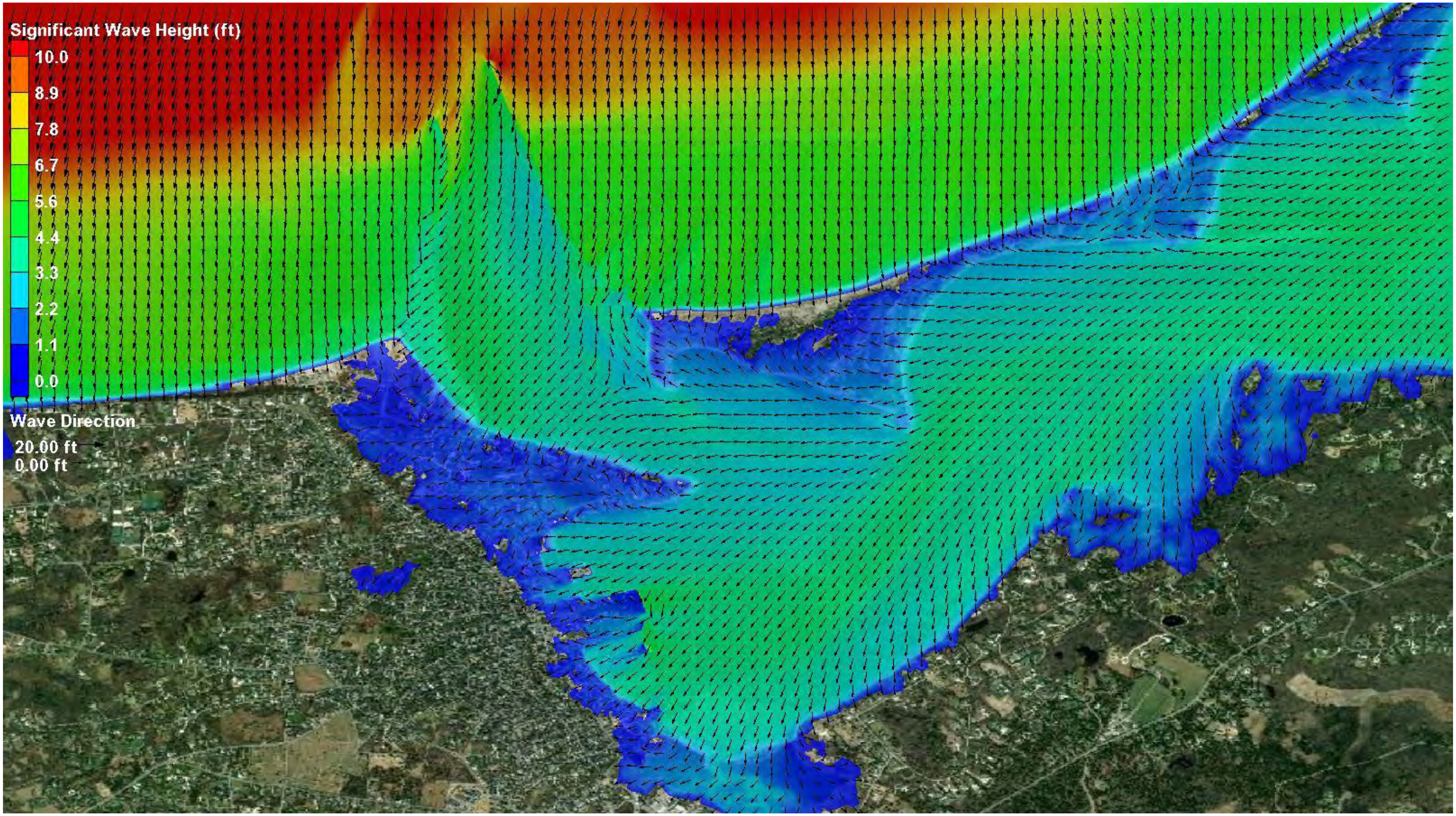

Significant Wave Height (ft)
15.0
13.3
11.7
10.0
8.3
6.7
5.0
3.3
1.7
0.0
Wave Direction
20.00 ft
0.00 ft

Figure 5



Significant Wave Height (ft)
10.0
8.9
7.8
6.7
5.6
4.4
3.3
2.2
1.1
0.0
Wave Direction
20.00 ft
0.00 ft

Figure 6

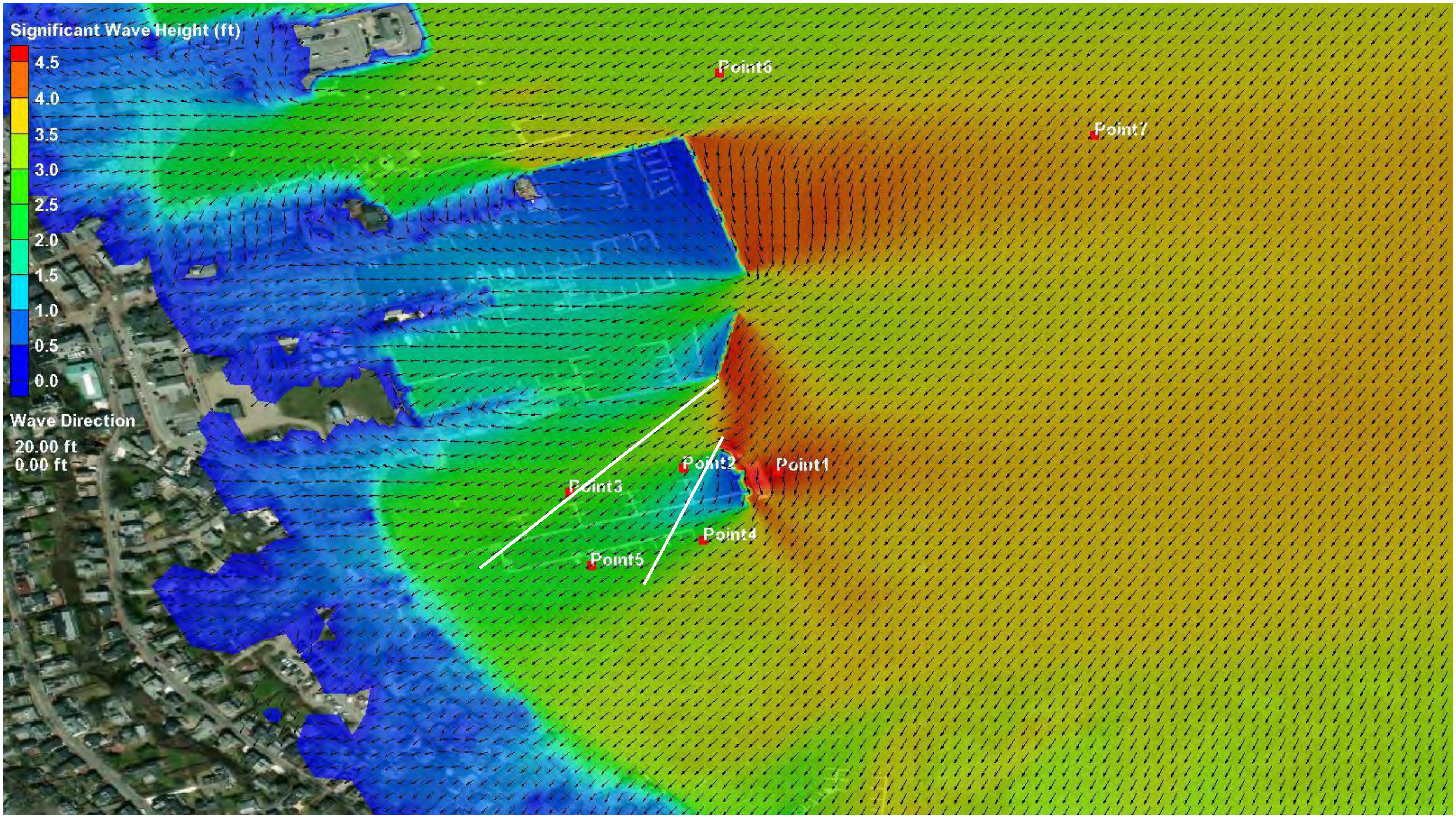


Figure 7 (White lines indicate the zone of increased wave height due to structure effects "Storm Damage Cone" observed by Town)

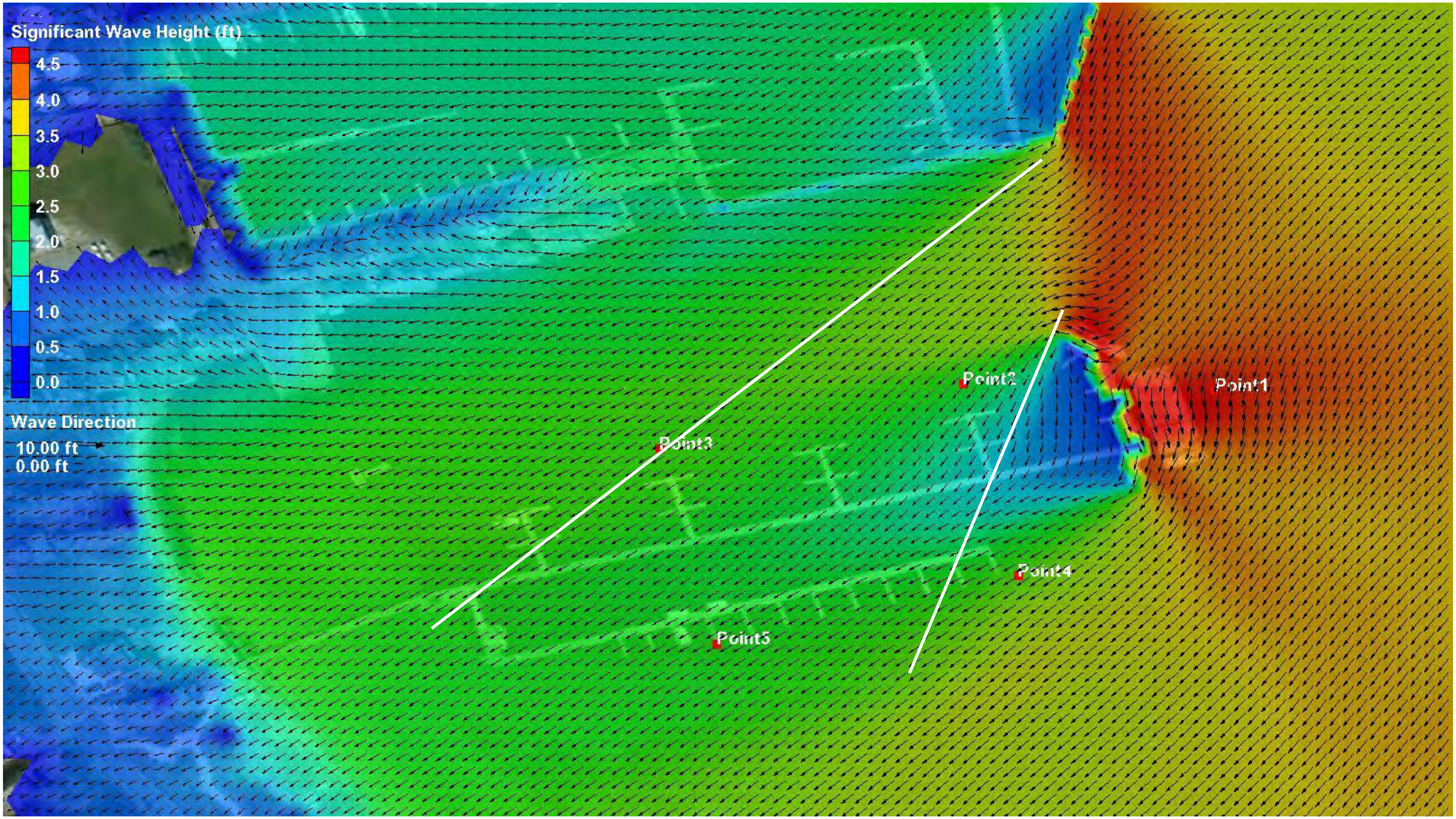


Figure 8 (White lines indicate the zone of increased wave height due to structure effects "Storm Damage Cone" observed by Town)

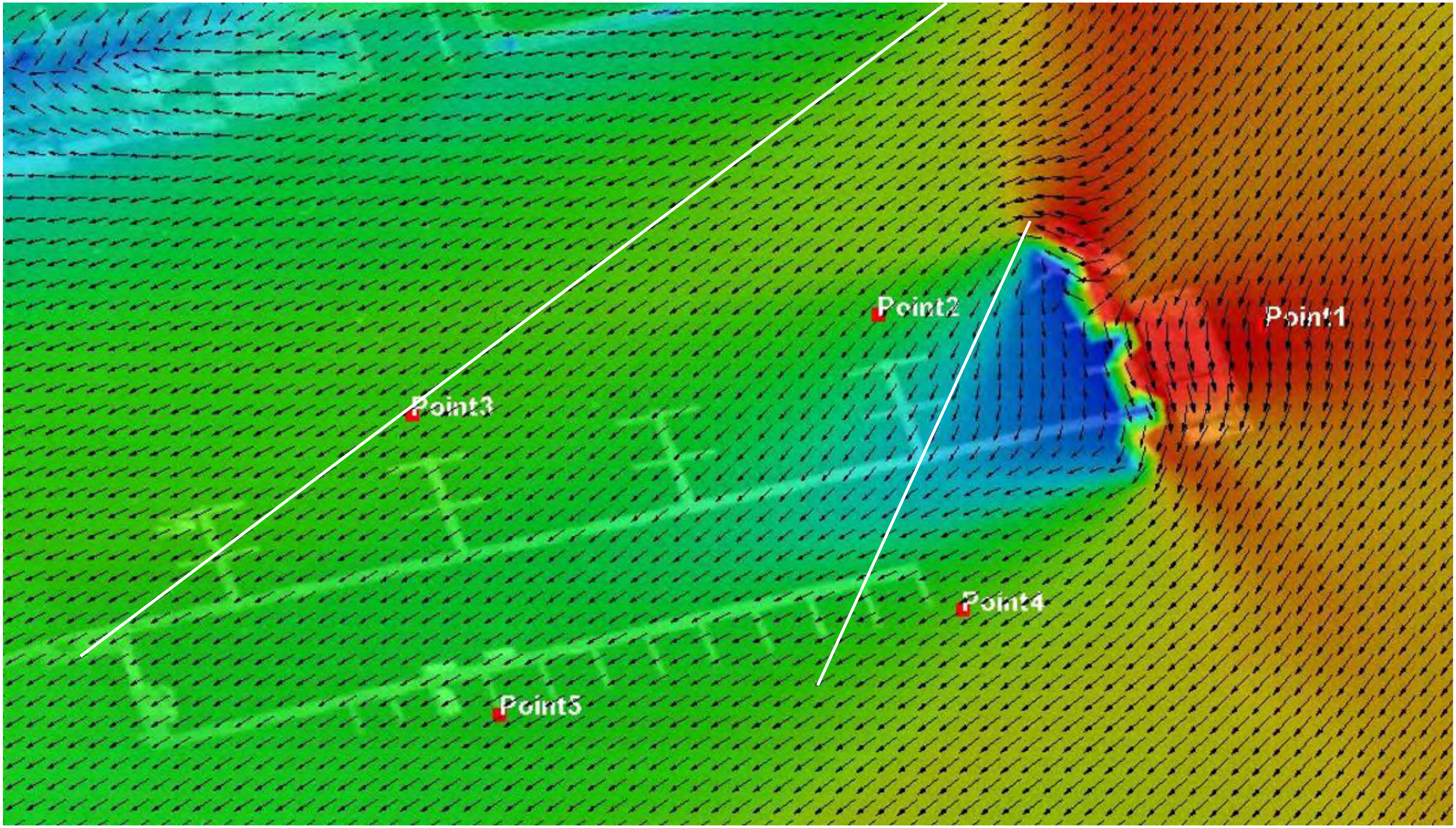


Figure 9 (White lines indicate the zone of increased wave height due to structure effects "Storm Damage Cone" observed by Town)

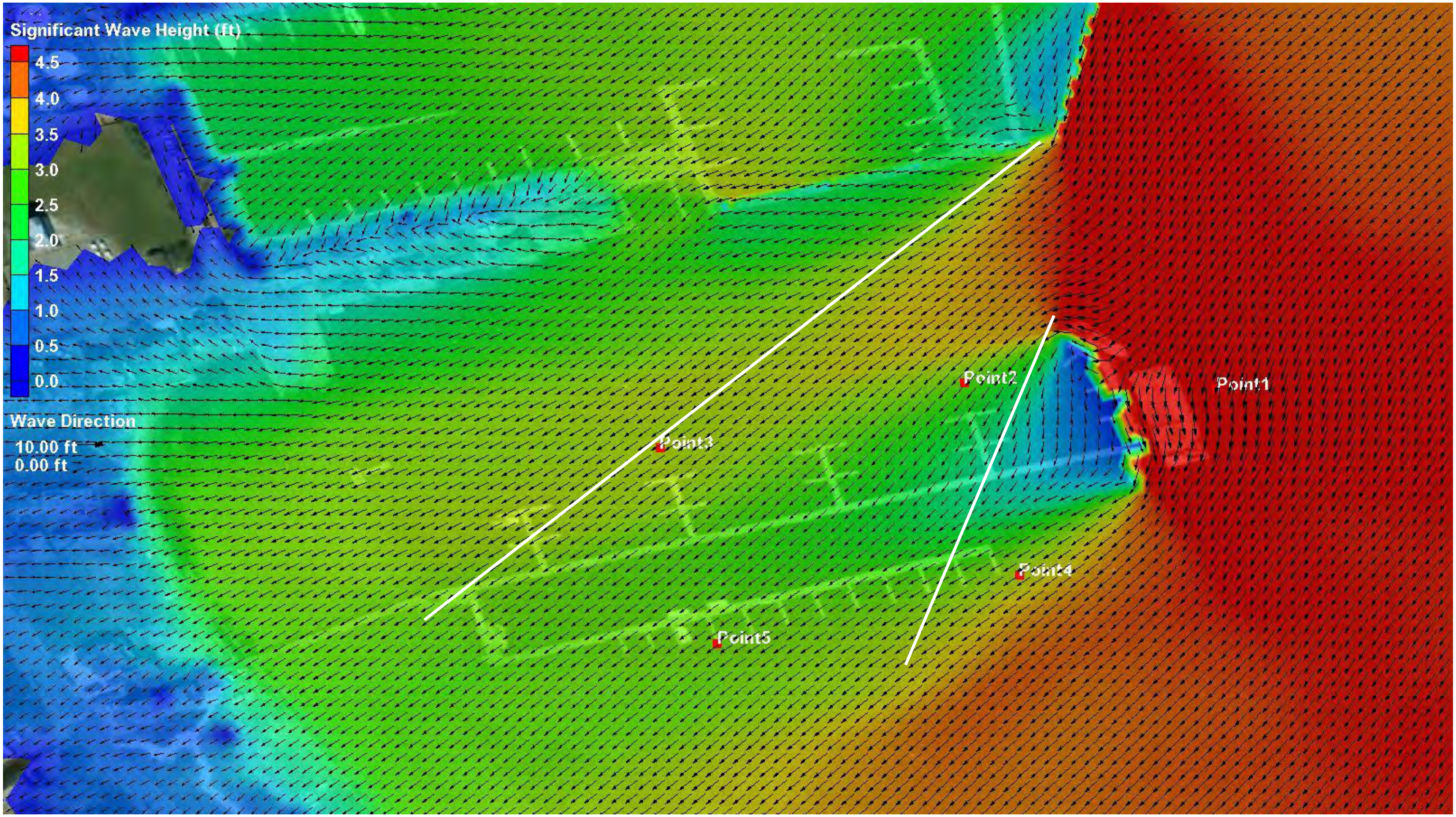


Figure 10: Existing Wave Fence during 100-year recurrence interval event with 98mph 1-minute sustained northeast wind and Elevation 6 feet NAVD88 Stillwater Elevation (White lines indicate the zone of increased wave height due to structure effects "Storm Damage Cone" observed by Town)

Figure 11: Considered Wave Fence Extension. Structure improvements/modifications under consideration including extension of the existing Town Pier wave fence approximately 45 to the north and about 60 feet to the south.

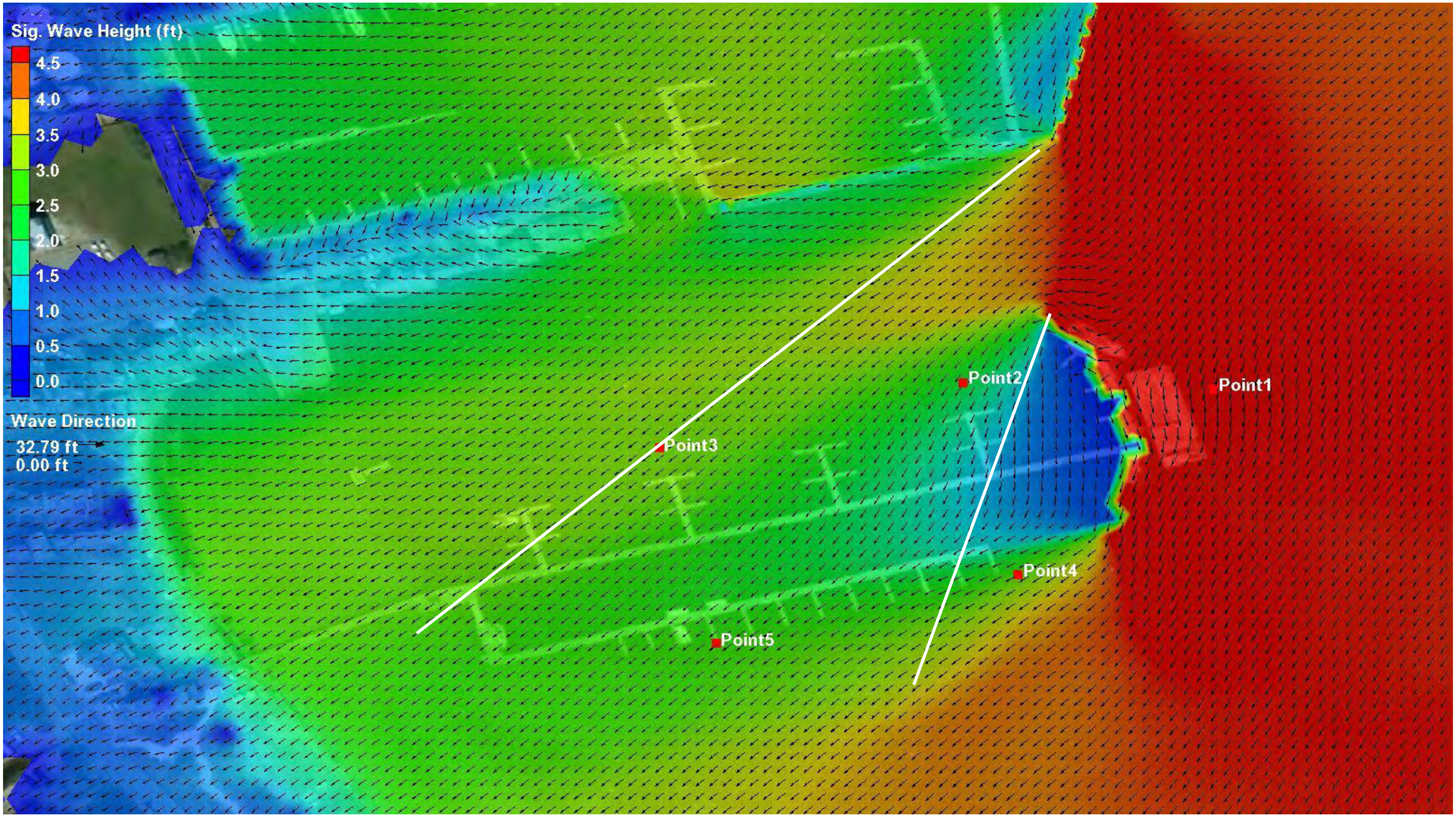


Figure 12: Considered Wave Fence Extension. 100-year recurrence interval event with 98mph 1-minute sustained northeast wind and Elevation 6 feet NAVD88 Stillwater Elevation. Structure improvements/modifications under consideration including extension of the existing Town Pier wave fence approximately 45 to the north and about 60 feet to the south. (White lines indicate the zone of increased wave height due to structure effects "Storm Damage Cone" currently observed by Town – shown for reference)

Figure 13: Considered Wave Fence Extension. Structure improvements/modifications under consideration including extension of the existing Town Pier wave fence approximately 100 feet to the north.

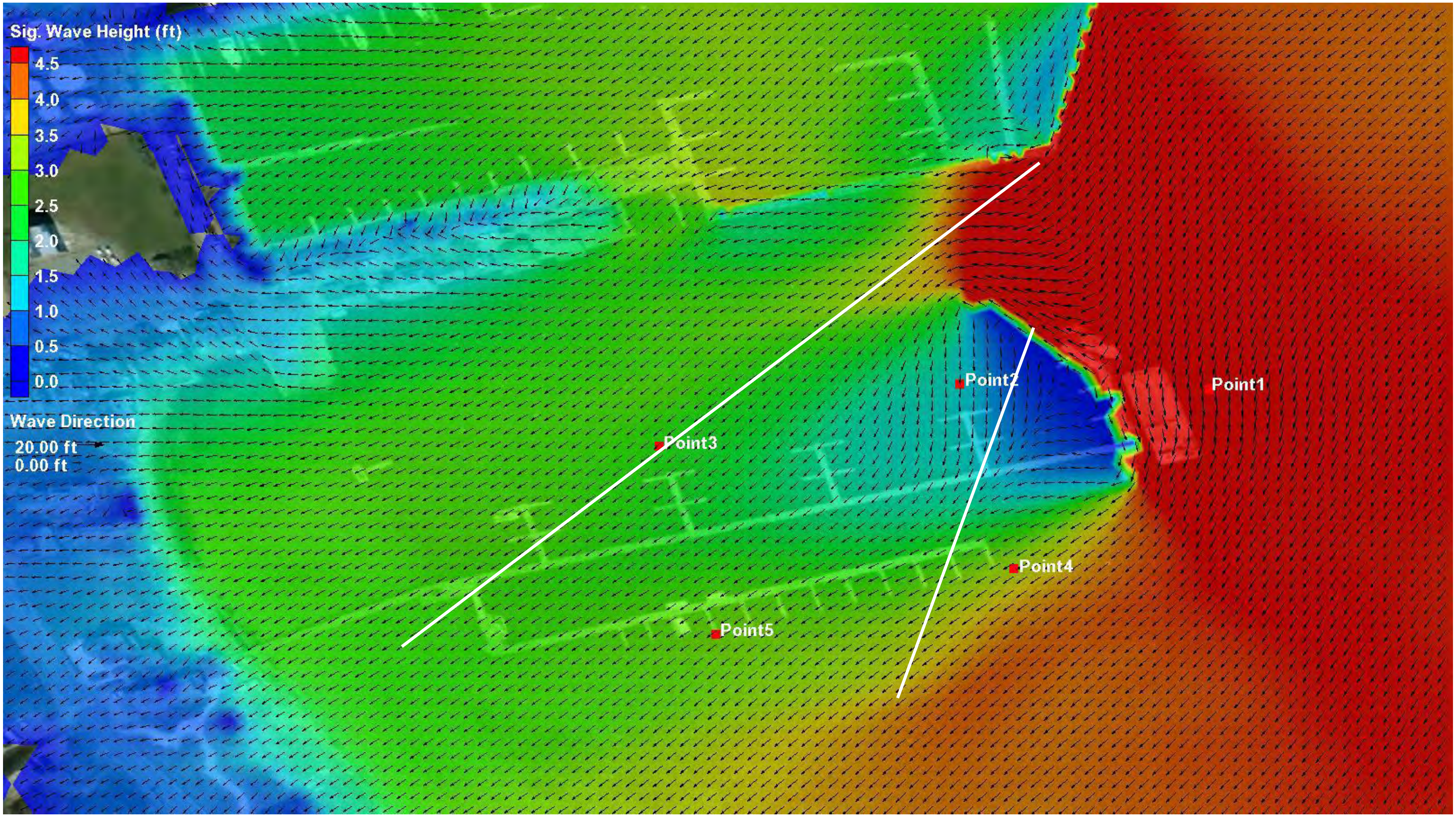


Figure 14: Considered Wave Fence Extension. Structure improvements/modifications under consideration including extension of the existing Town Pier wave fence approximately 100 feet to the north. 100-year recurrence interval event with 98mph 1-minute sustained northeast wind and Elevation 6 feet NAVD88 Stillwater Elevation. (White lines indicate the zone of increased wave height due to structure effects "Storm Damage Cone" currently observed by Town – shown for reference)

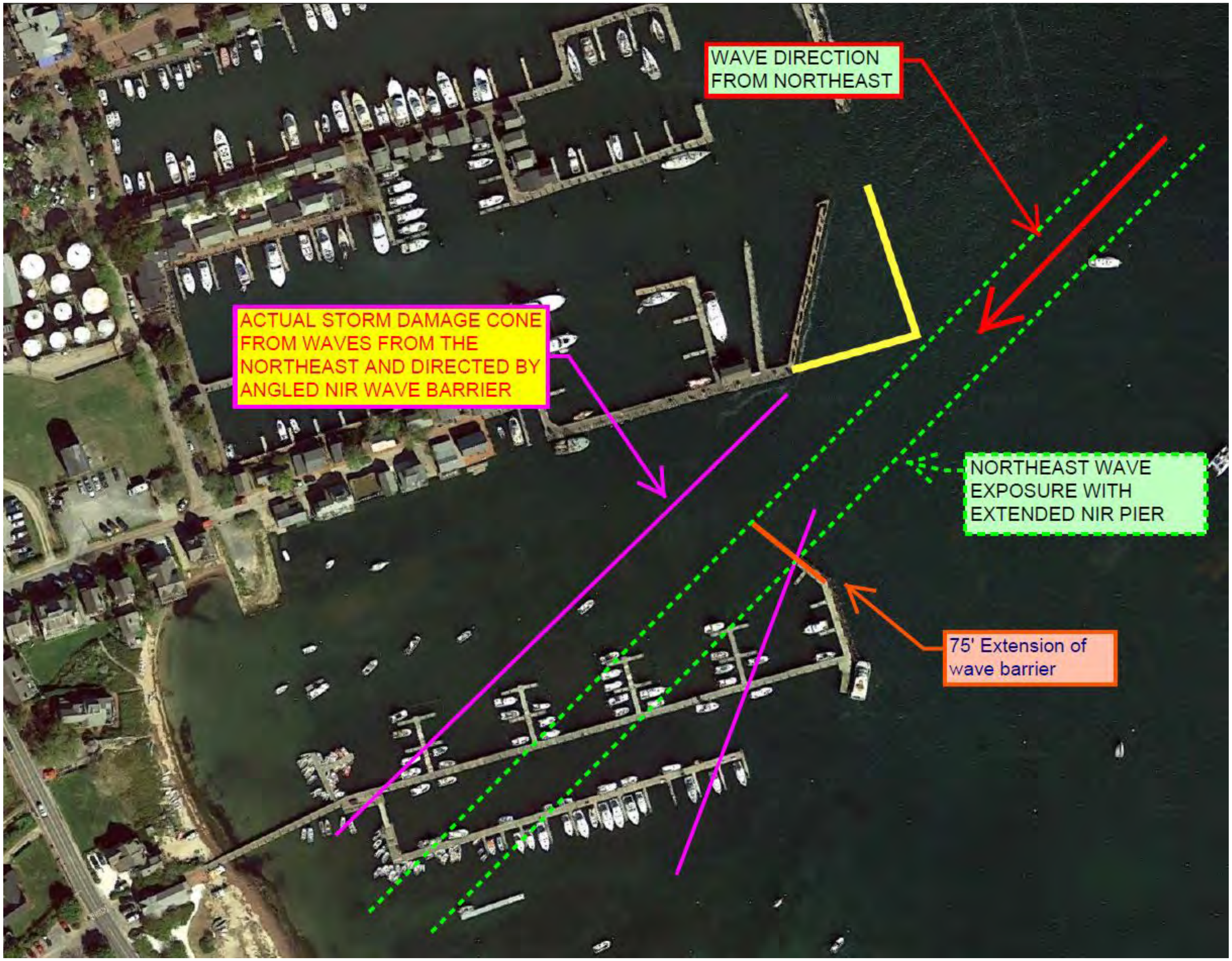


Figure 15: Structure improvements/modifications under consideration including: 1) extension of the existing Town Pier wave fence; and 2) extension of Nantucket Boat Basin. (Purple lines indicate the zone of currently observed increased wave height due to structure effects "Storm Damage Cone" – shown for reference). Image prepared and provided by Town.

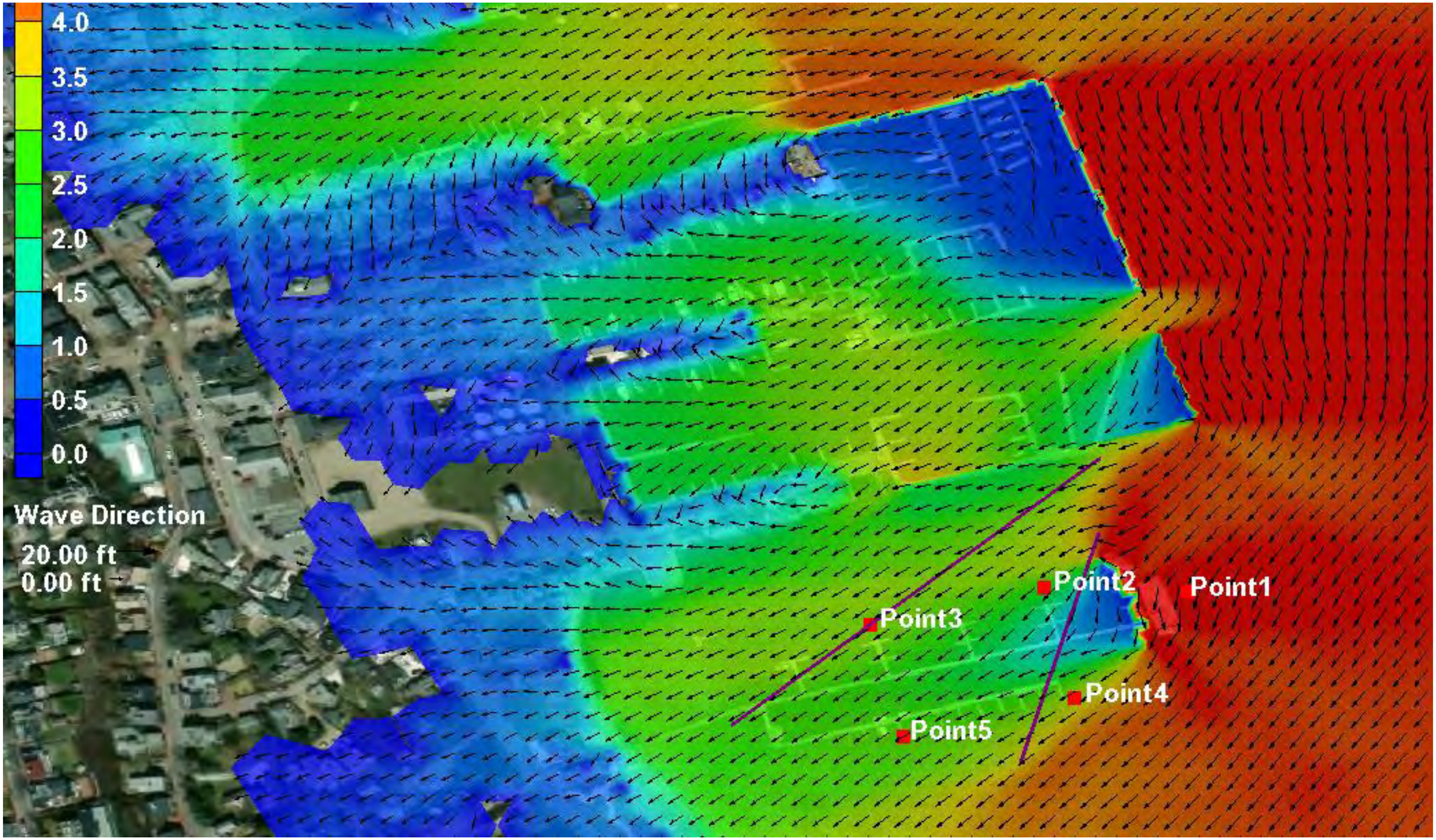


Figure 16: Significant Wave Height simulated by SWAN Wave Model for Run #13F. Structure improvements/modifications under consideration including extension of Nantucket Boat Basin with No Change to Town Pier. (Purple lines indicate the zone of currently observed increased wave height due to structure effects "Storm Damage Cone" currently observed by Town – shown for reference).

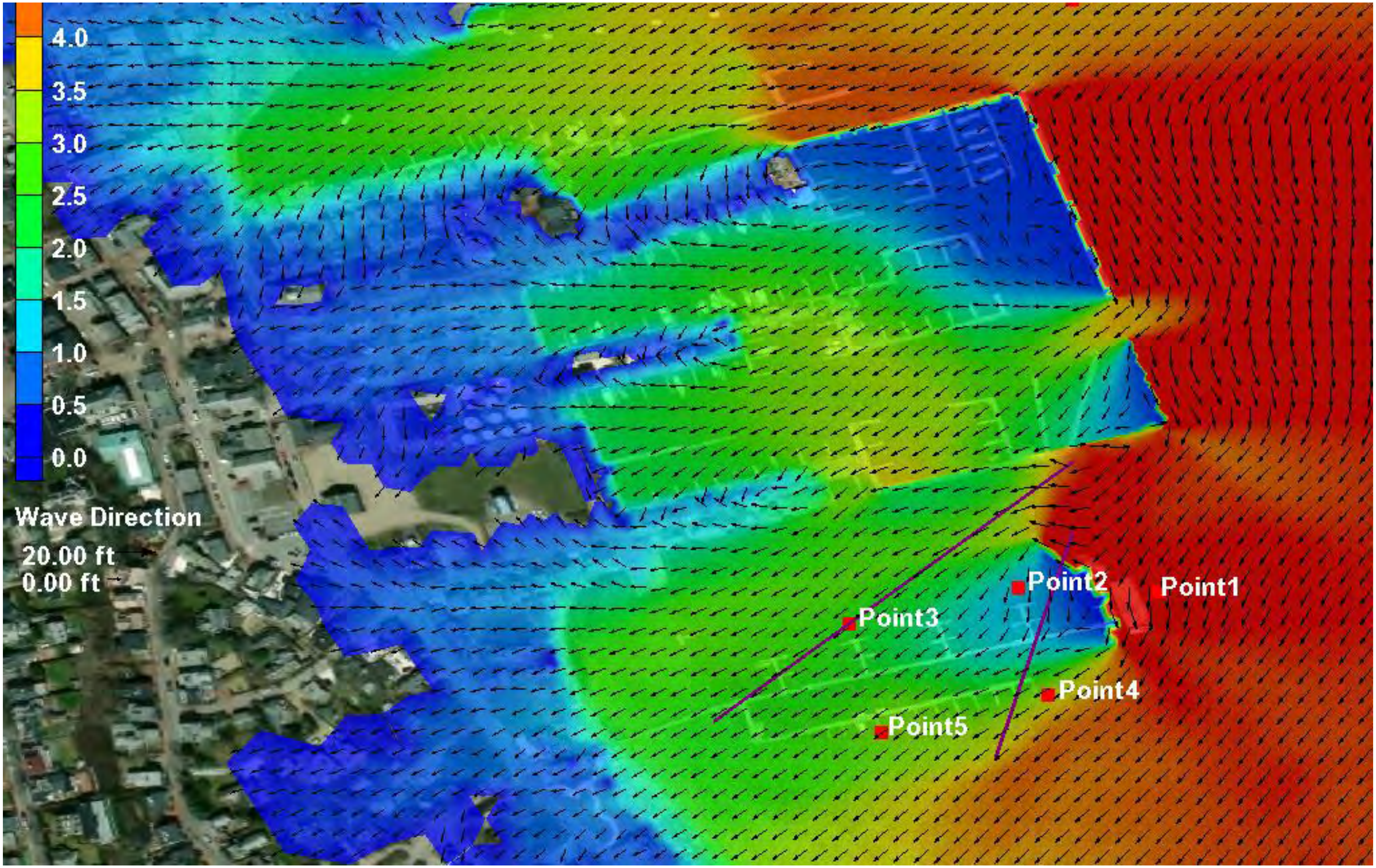
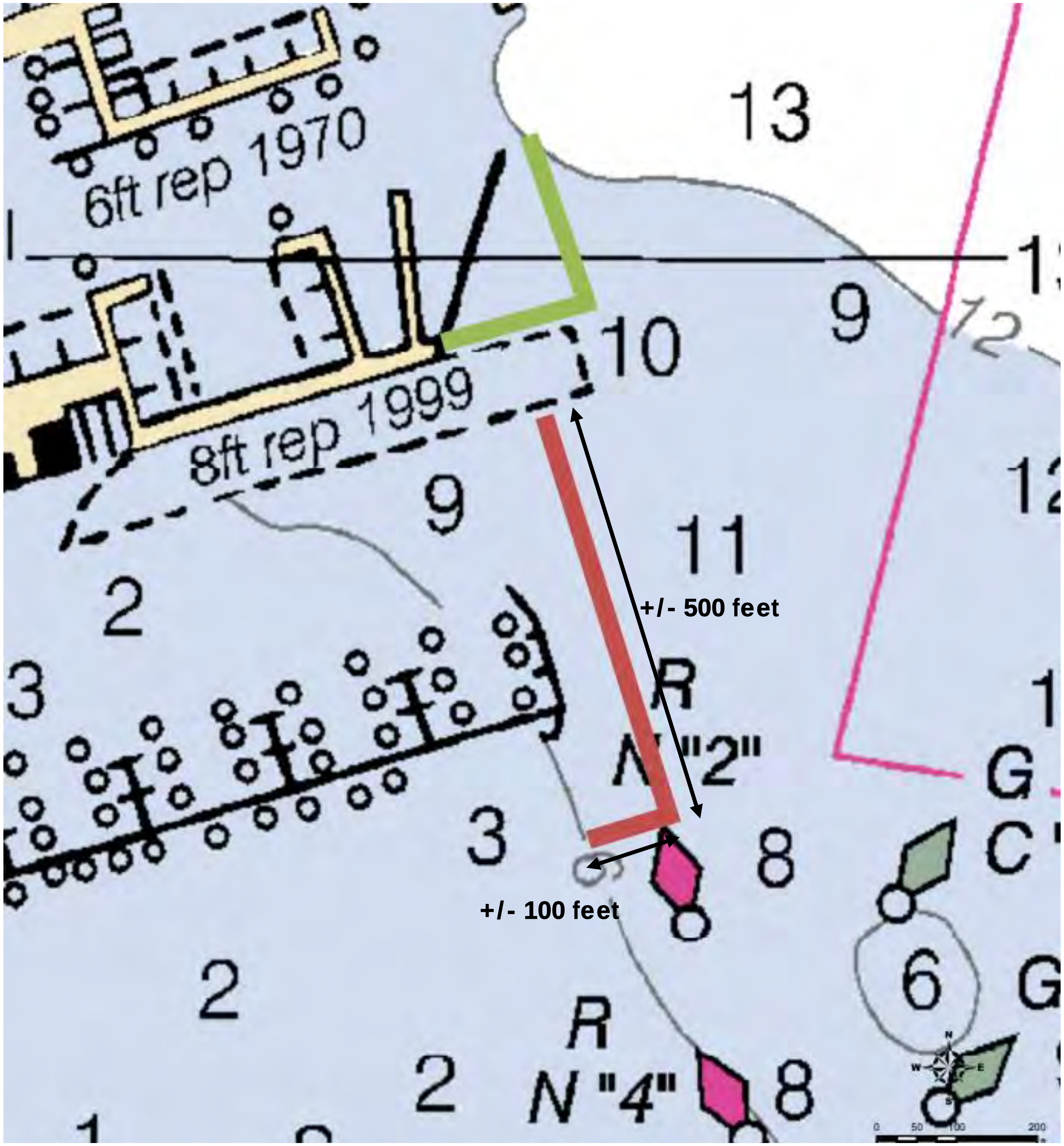
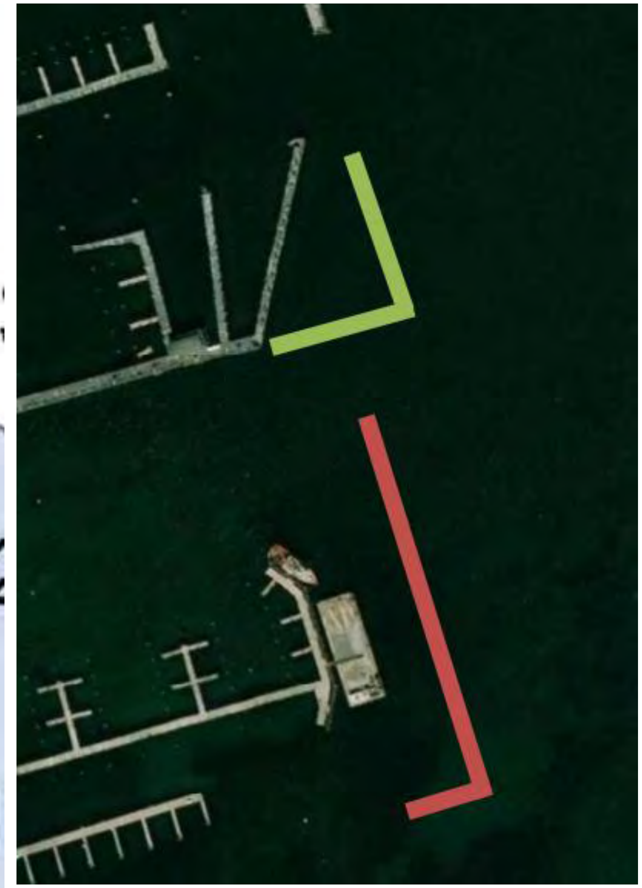


Figure 17: Significant Wave Height simulated by SWAN Wave Model for Run #13F. Structure improvements/modifications under consideration including extension of Nantucket Boat Basin with about north 100-foot extension to Town Pier. (Purple lines indicate the zone of increased wave height due to structure effects "Storm Damage Cone" currently observed by Town – shown for reference).





(insert showing wave attenuator relative to Town Pier floating dock)

Figure 18: Town Pier Wave Attenuator Alternative. Structure improvements/modifications under consideration including extension of Nantucket Boat Basin with a separate Town Pier Wave Attenuator (floating dock).

ATTACHMENT 1
Tide Datums

NOTICE: All data values are relative to the MLLW.

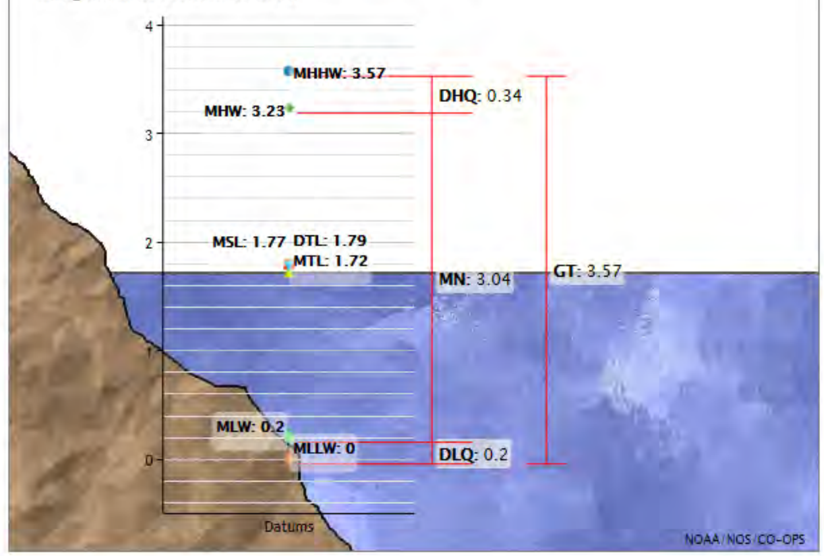
Elevations on Mean Lower Low Water

Station: 8449130, Nantucket Island, MA
Status: Accepted (Apr 17 2003)
Units: Feet
Control Station:

T.M.: 0
Epoch: 1983-2001
Datum: MLLW

Datum	Value	Description
MHHW	3.57	Mean Higher-High Water
MHW	3.23	Mean High Water
MTL	1.72	Mean Tide Level
MSL	1.77	Mean Sea Level
DTL	1.79	Mean Diurnal Tide Level
MLW	0.20	Mean Low Water
MLLW	0.00	Mean Lower-Low Water
NAVD88		
STND	-3.00	Station Datum
GT	3.57	Great Diurnal Range
MN	3.04	Mean Range of Tide
DHQ	0.34	Mean Diurnal High Water Inequality
DLQ	0.20	Mean Diurnal Low Water Inequality
HWI	4.87	Greenwich High Water Interval (in hours)
LWI	10.64	Greenwich Low Water Interval (in hours)
Max Tide	7.87	Highest Observed Tide
Max Tide Date & Time	10/30/1991 17:30	Highest Observed Tide Date & Time
Min Tide	-2.14	Lowest Observed Tide
Min Tide Date & Time	02/12/1981 12:30	Lowest Observed Tide Date & Time
HAT	4.41	Highest Astronomical Tide
HAT Date & Time	11/14/1989 17:24	HAT Date and Time
LAT	-0.82	Lowest Astronomical Tide
LAT Date & Time	04/27/1994 11:42	LAT Date and Time

Datums for 8449130, Nantucket Island, MA
All figures in feet relative to MLLW



Showing datums for

8449130 Nantucket Island, MA

Data Units ◉ Feet ○ Meters

Epoch ◉ Present (1983-2001) ○ Superseded (1960-1978)

Submit

Station Info ▾ | Tides/Water Levels ▾ | Meteorological Obs. | Phys. Oceanography

Nantucket Island, MA - Station ID: 8449130

Station Info | Today's Tides | Photos | Sensor Information | Observations | Directions and Map | Available Products

Established:	Oct 04, 1963
Time Meridian:	0° E
Present Installation:	Sep 18, 1990
Date Removed:	N/A
Water Level Max (ref MHHW):	4.30 ft. Oct 30, 1991
Water Level Min (ref MLLW):	-2.14 ft. Feb 12, 1981
Mean Range:	3.04 ft.
Diurnal Range:	3.57 ft.
Latitude	41° 17.1' N
Longitude	70° 5.8' W
NOAA Chart#:	13241
Met Site Elevation:	7.1 ft. above MSL

Today's Tides (LST)

next tide at
2:00 PM
high

2:11 AM	high	2.7 ft.
7:27 AM	low	0.6 ft.
2:00 PM	**high**	**3.5 ft.**
8:16 PM	low	0.0 ft.

Nantucket Island, MA

7 more station photos available, click to view.

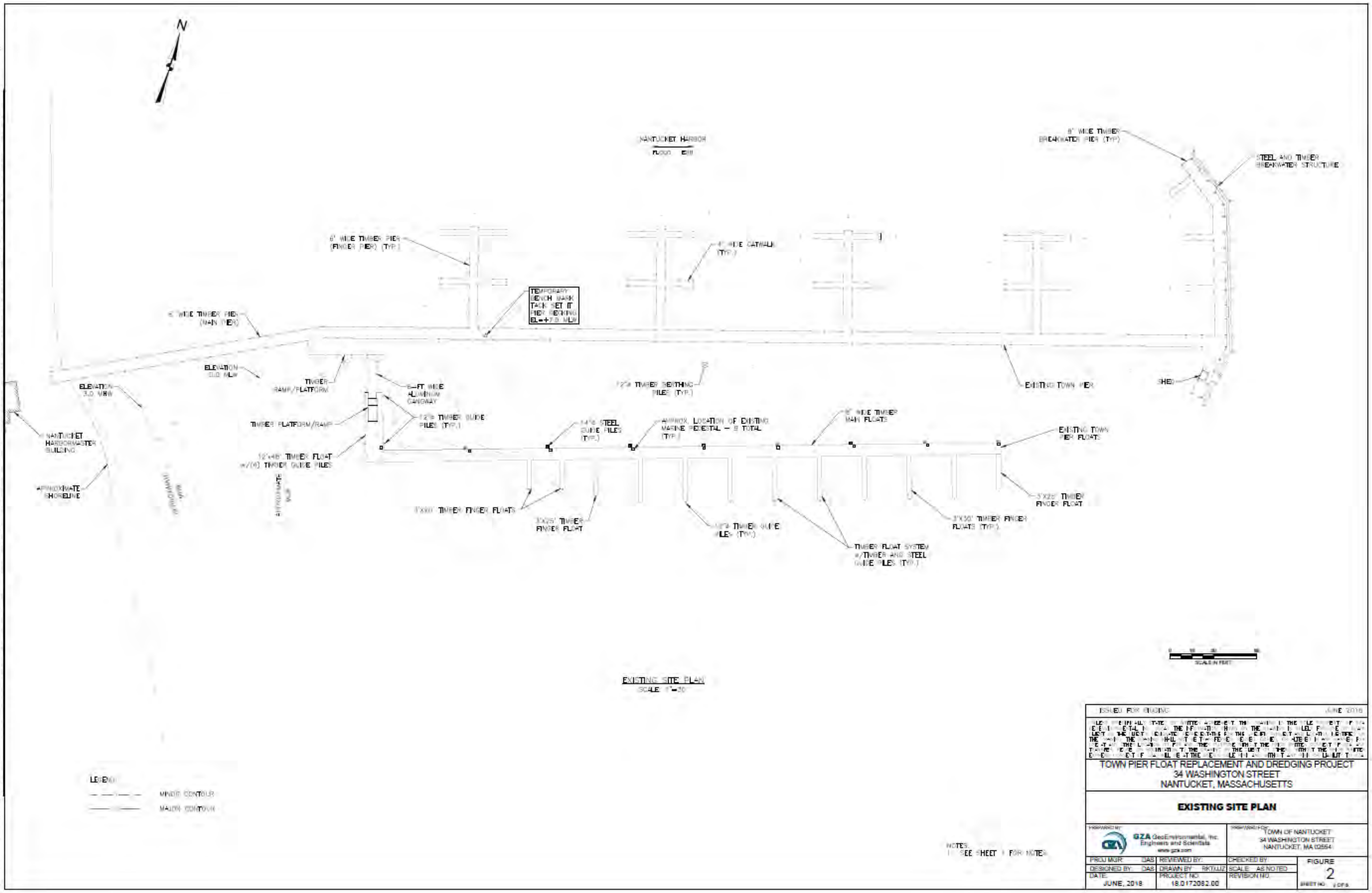
	ft-MLLW	ft-NAVD88
MHHW	3.57	1.53
MHW	3.23	1.19
NAVD88	2.04	0
MSL	1.77	-0.27
MTL	1.72	-0.32
MLW	0.2	-1.84
MLLW	0	-2.04

Notes:

1. Tidal Elevations are based on datum at NOAA Tidal Station 8449130, Nantucket Island MA
2. Datum of NAVD88 with respect to MLLW is based on VDatum at NOAA Tidal Station 8449130, Nantucket Island MA.

Table 1: Tidal Elevation Datums at NOAA Tidal Station 8449130 at Nantucket (feet, Mean Lower Low Water and NAVD88)

ATTACHMENT 2
Existing Pier Details


N
NANTUCKET HARBOR
6' WIDE TIMBER BREAKWATER PIER (TYP.)
STEEL AND TIMBER BREAKWATER STRUCTURE
6' WIDE TIMBER PIER (FINGER PIER) (TYP.)
4' WIDE CATWALK (TYP.)
TEMPORARY BENCH MARK TACK SET IN PIER DECKING EL=+7.0 MLW
WIDE TIMBER PIER (MAIN PIER)
ELEVATION 0.0 MLW
ELEVATION 3.0 MHW
TIMBER RAMP/PLATFORM
6-FT WIDE ALUMINUM GANGWAY
12"ø TIMBER BERTHING PILES (TYP.)
EXISTING TOWN PIER
SHED
TIMBER PLATFORM/RAMP
12"ø TIMBER GUIDE PILES (TYP.)
14"ø STEEL GUIDE PILES (TYP.)
APPROX. LOCATION OF EXISTING MARINE PEDESTAL – 9 TOTAL (TYP.)
8' WIDE TIMBER MAIN FLOATS
EXISTING TOWN PIER FLOATS
NANTUCKET HARBORMASTER BUILDING
12'x48' TIMBER FLOAT w/(4) TIMBER GUIDE PILES
APPROXIMATE SHORELINE
TIMBER FINGER FLOATS
3'X25' TIMBER FINGER FLOAT
12"ø TIMBER GUIDE PILES (TYP.)
TIMBER FLOAT SYSTEM w/TIMBER AND STEEL GUIDE PILES (TYP.)
3'X30' TIMBER FINGER FLOATS (TYP.)
3'X25' TIMBER FINGER FLOAT
SCALE IN FEET
EXISTING SITE PLAN
LEGEND:
MINOR CONTOUR
MAJOR CONTOUR
NOTES:
1. SEE SHEET 1 FOR NOTES.
ISSUED FOR BIDDING
JUNE 2018
TOWN PIER FLOAT REPLACEMENT AND DREDGING PROJECT
34 WASHINGTON STREET
NANTUCKET, MASSACHUSETTS
EXISTING SITE PLAN
PREPARED BY:
GZA GeoEnvironmental, Inc.
Engineers and Scientists
www.gza.com
PREPARED FOR:
TOWN OF NANTUCKET
34 WASHINGTON STREET
NANTUCKET, MA 02554
PROJ MGR: DAS
REVIEWED BY:
CHECKED BY:
FIGURE
DESIGNED BY: DAS
DRAWN BY: RKT/JJZ
SCALE: AS NOTED
2
DATE:
JUNE, 2018
PROJECT NO.
18.0172082.00
REVISION NO.
SHEET NO.

ATTACHMENT 3
Historic Storm Data

HISTORIC STORM TYPES

GZA evaluated historic storm data and sources for historic extreme water levels (due to storm surge) and ocean wave data. The purpose of this evaluation was to inform the recommendation for design environmental conditions.

In general, combined storm surge, waves and high wind at Nantucket occurs due to two storm types: 1) tropical cyclones, including tropical storms and hurricanes; and 2) extratropical low pressure systems (nor'easters).

Hurricanes are relatively rare in the vicinity of Nantucket but can result in extreme wind, waves and elevated water levels due to storm surge. There can be high intensity, but are typically of short duration. Exceptions to this are hybrid storms (e.g., Superstorm Sandy, the "Perfect Storm") which consist of both tropical and extratropical components and can result in large windfields and longer duration. The effect of hurricanes on Nantucket are a function of: 1) recurrence rate (i.e., the frequency that hurricanes occur in the vicinity of Nantucket); 2) the storm track relative to the island (considering that hurricanes occur with a counterclockwise wind direction); and 3) the combination of meteorological parameters that determine the storm's translation speed, radius of maximum wind and intensity (central pressure deficit and wind speed). Different areas of the island will be effected differently, dependent upon the storm track. In particular relative to the Town Pier (which is most vulnerable to winds coming from the north to east), a hurricane would have to track to the southeast of the island and within 25 to 40 miles to get a maximum wind velocity coming from the north to east (aligned with the fetch of the pond). This is a relatively infrequent event.

Nor'easters are extratropical storms, generally occurring during the months of November through April. These storms are relatively frequent events, occurring several times a year. Nor'easters are typically of less intensity than hurricanes, but of longer duration, lasting several tide cycles. In New England, nor'easters occur as synoptic low pressure systems migrating in a northeast direction up the coast from the Caribbean or from the Great Lakes region in a west to east direction. A common characteristic of nor'easters is that the dominant wind comes from the north to east quadrant. This wind direction is in alignment with the fetch of the pond and Nantucket Harbor.

Severe wind at Nantucket can also occur due to severe thunderstorms or (rarely) tornados. These are short duration events, with wind from any direction but do not typically result in an elevated water level or an extended period of waves.

The following provides an overview of historic tropical cyclones and nor'easters in the vicinity of Nantucket based on available NOAA and National Weather Service data. The top storm events (in terms of water levels at the NOAA Nantucket tidal station and nearby ocean waves). Storm track and meteorological data (if available) are presented for key, representative storms. Statistical analyses of water level and wave data are presented, and the top ten events and storm type (within the period of record are identified.

As presented in the following pages, elevated water levels, high winds and large ocean waves within the period of record (53 years of water level data and 34 years of wave data) are predominantly associated with extratropical nor'easters. This is due to the lack of occurrence of hurricanes with track direction, storm intensity and proximity to Nantucket to result in elevated (storm surge) water levels and high winds over the island during this period of record. This means that statistical interpretation of the historical wind and water level data, performed to develop design environmental conditions (up to the 100-year recurrence interval), are representative almost exclusively of extratropical storms. (Hurricanes have occurred within the period of record that likely resulted in large waves along the west, south and east shores but did not result in significant storm surges or high winds at Nantucket.)

Even though there has been a lack of impactful hurricanes within the 53 to 34 period of water level and wave record, an evaluation of hurricane track data (HURDAT2) identifies a number of intense hurricanes within the HURDAT2 period of record (+/- 1850s to current). These hurricanes are discussed below. In general, the hurricane recurrence interval within the Nantucket strike zone is about 13 years and the recurrence interval of major hurricanes within the Nantucket strike zone is about 62 years.

Attachment 4 presents a detailed statistical wind analysis, including statistical analysis of wind data from Nantucket airport. **Attachment 5** presents a detailed statistical water level analysis, including statistical analysis of water level data from the NOAA tidal station.

Historic Hurricanes in the Vicinity of Nantucket

Hurricanes, tropical storms and tropical depressions are tropical cyclones - rotating low pressure weather systems that have organized thunderstorms but no pressure fronts (a boundary separating two air masses of different densities). Tropical cyclones with maximum sustained surface winds of less than 39 miles per hour (mph) are called tropical depressions. Those with maximum sustained winds between 39 mph and 73 mph are tropical storms. Hurricanes are tropical cyclones with sustained wind speeds of 74 mph or higher. The Saffir-Simpson Hurricane Wind Scale is a 1 to 5 rating, or category, based on a hurricane's maximum sustained winds. The higher the category, the greater the hurricane's potential for property damage (NOAA National Ocean Service). A major hurricane (Categories 3, 4 and 5) has sustained wind speeds of 111 mph or higher on the Saffir-Simpson Hurricane Wind Scale.

(for 1-minute maximum sustained winds)

Tropical storm	18–32 m/s	34–63 kn	39–73 mph	63–118 km/h
Tropical depression	≤ 17 m/s	≤ 33 kn	≤ 38 mph	≤ 62 km/h

Saffir–Simpson scale

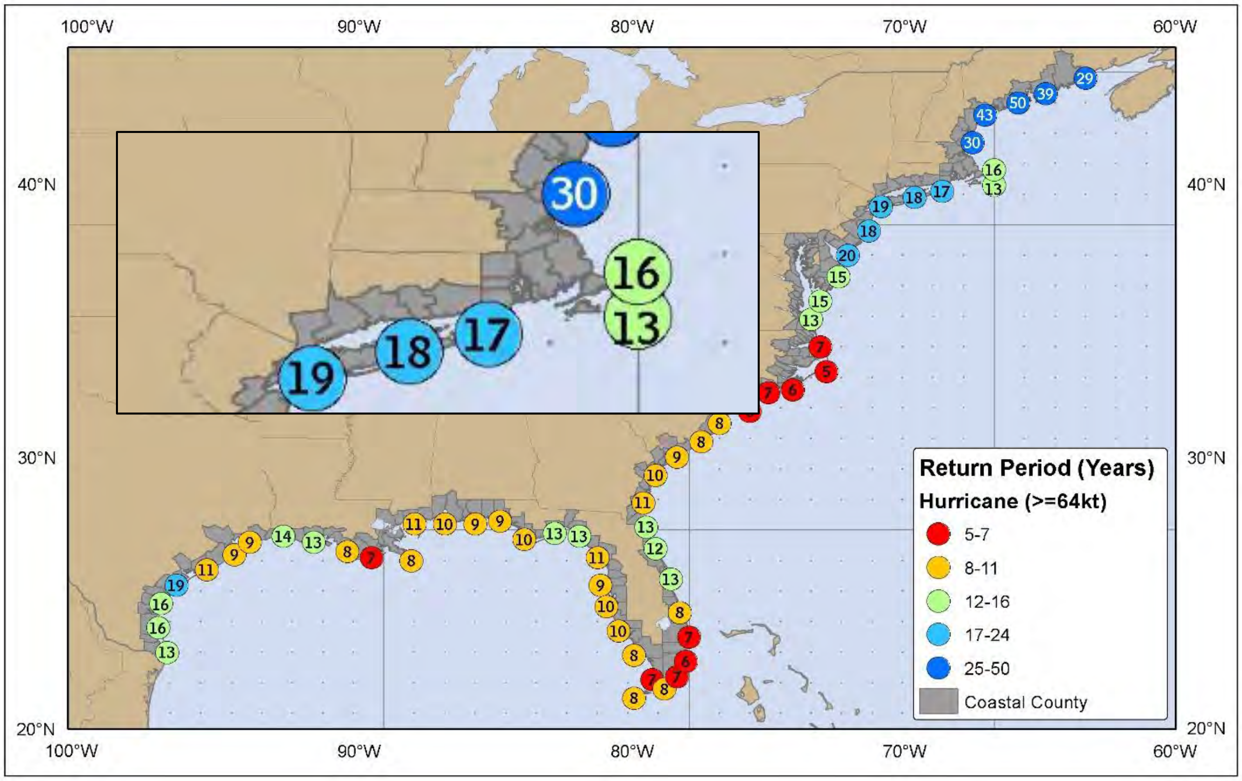
Category	Wind speeds (for 1-minute maximum sustained winds)			
	m/s	knots (kn)	mph	km/h
Five	≥ 70 m/s	≥ 137 kn	≥ 157 mph	≥ 252 km/h
Four	58–70 m/s	113–136 kn	130–156 mph	209–251 km/h
Three	50–58 m/s	96–112 kn	111–129 mph	178–208 km/h
Two	43–49 m/s	83–95 kn	96–110 mph	154–177 km/h
One	33–42 m/s	64–82 kn	74–95 mph	119–153 km/h

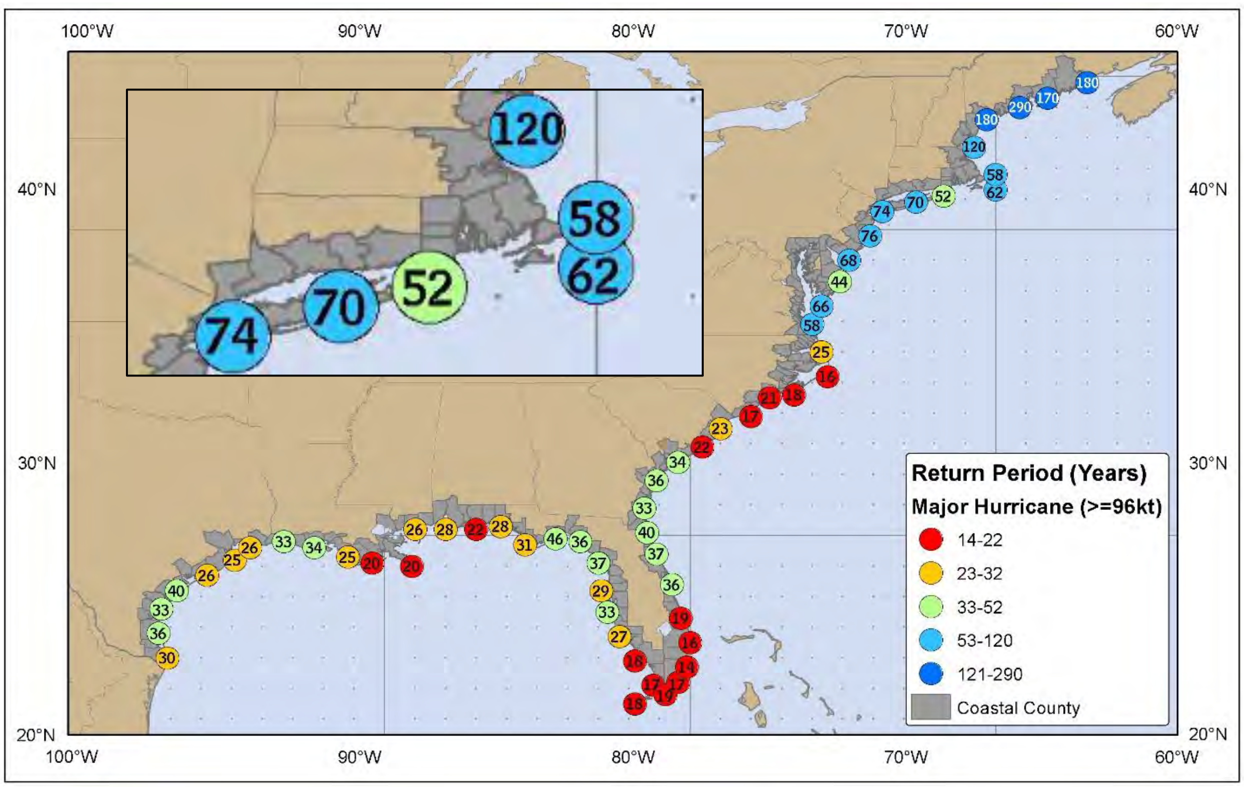
East Coast hurricanes originate in the Atlantic basin, which includes the Atlantic Ocean, Caribbean Sea, and Gulf of Mexico. A six-year rotating list of names, updated and maintained by the World Meteorological Organization, is used to identify these storms. "Hurricane Season" begins on June 1 and ends on November 30, although hurricanes can, and have, occurred outside of this time frame (NOAA National Ocean Service).

Hurricane return periods are the frequency at which a certain intensity of hurricane can be expected within a given distance of a given location (for the below images 50 nm or 58 statute miles). In simpler terms, a return period of 20 years for a major hurricane means that *on average* during the previous 100 years, a Category 3 or greater hurricane passed within 50 nm (58 miles) of that location about five times. We would then expect, *on average*, an additional five Category 3 or greater hurricanes within that radius over the next 100 years.

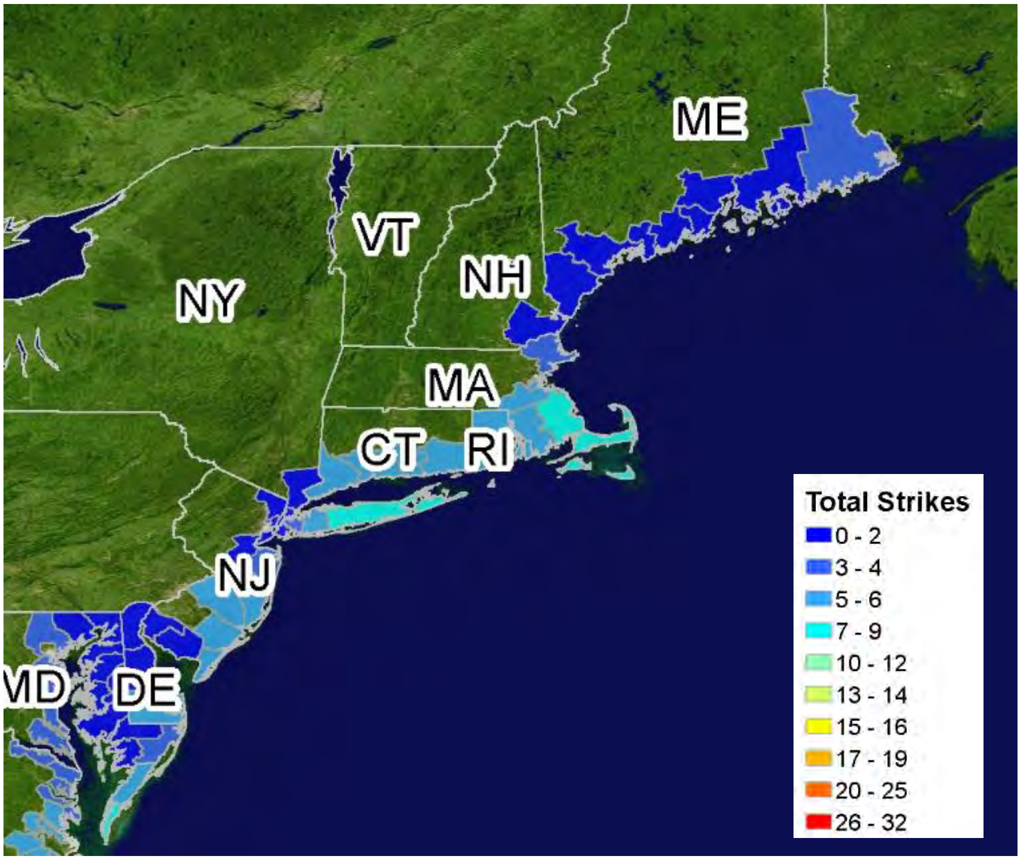
Based on available historic hurricane data available in the NOAA HURDAT2 database, the estimated hurricane (all categories) return period for the vicinity of Nantucket is about 13 years. The estimated hurricane return period for major hurricanes (category 3 and greater) in the vicinity of Nantucket is about 62 years. See **Figures 1** and **2** below.

For any particular location, a hurricane strike occurs if that location passes within the hurricane's strike circle, a circle of 125 n mi diameter, centered 12.5 n mi to the right of the hurricane center (looking in the direction of motion). This circle is meant to depict the typical extent of hurricane force winds, which are approximately 75 n mi to the right of the center and 50 n mi to the left. The observed number of hurricane strikes (by county) are presented in **Figures 3** (all category) and **4** (major hurricanes) for the time period of 1900 to 2010 (based on NOAA CONUS database). The observed number of hurricane strikes at Nantucket over this time period was 8. The observed number of hurricane strikes at Nantucket over this time period was 3.





Figures 1 and 2: Hurricane Recurrence Interval (all hurricanes - top and major hurricanes - bottom)
(Source: (Source: https://www.nhc.noaa.gov/climo/#bac



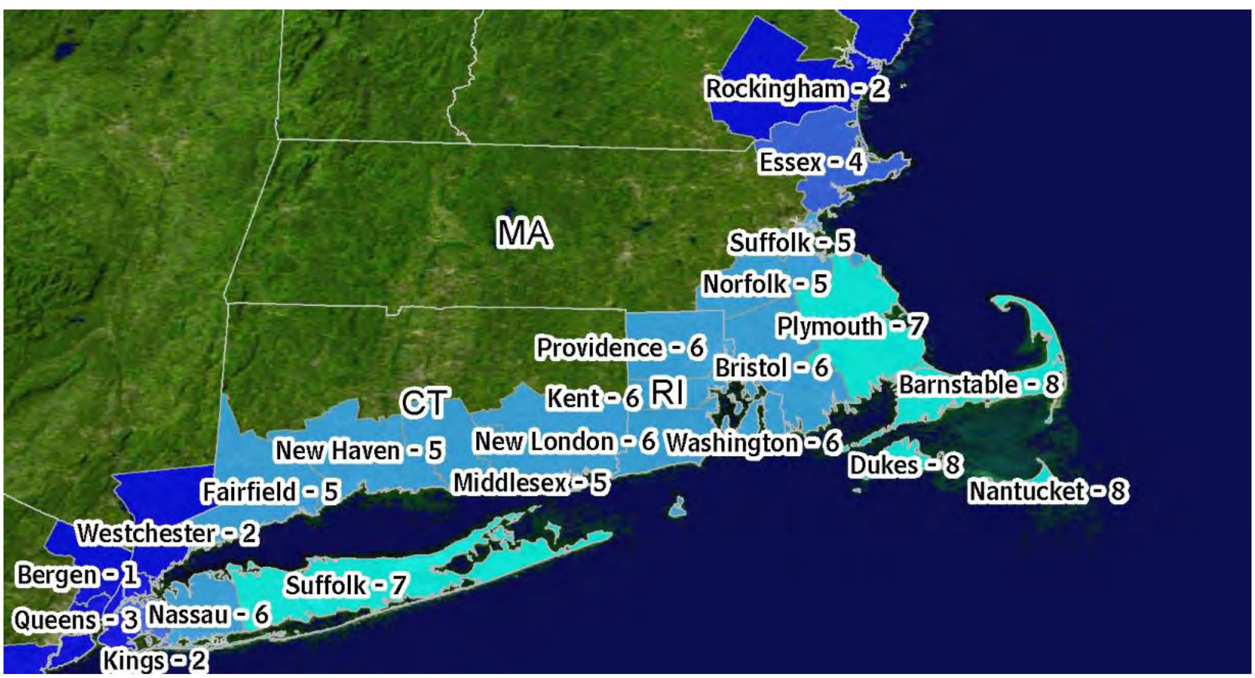


Figure 3: Hurricane Strikes between 1900 and 2010
(Source: (Source: https://www.nhc.noaa.gov/climo/#bac

Figure 3: Major Hurricane Strikes between 1900 and 2010
(Source: (Source: https://www.nhc.noaa.gov/climo/#bac

Historic hurricane and tropical storm tracks which have passed within 100 nautical miles of Nantucket (radius centered on Nantucket; the approximate hurricane strike zone for Nantucket)) were identified using the NOAA Hurricane Viewer (period of approximately 1850's to current) and are presented in **Figure 4**. A total of 87 events (including tropical storms and hurricanes) occurred within this radius.

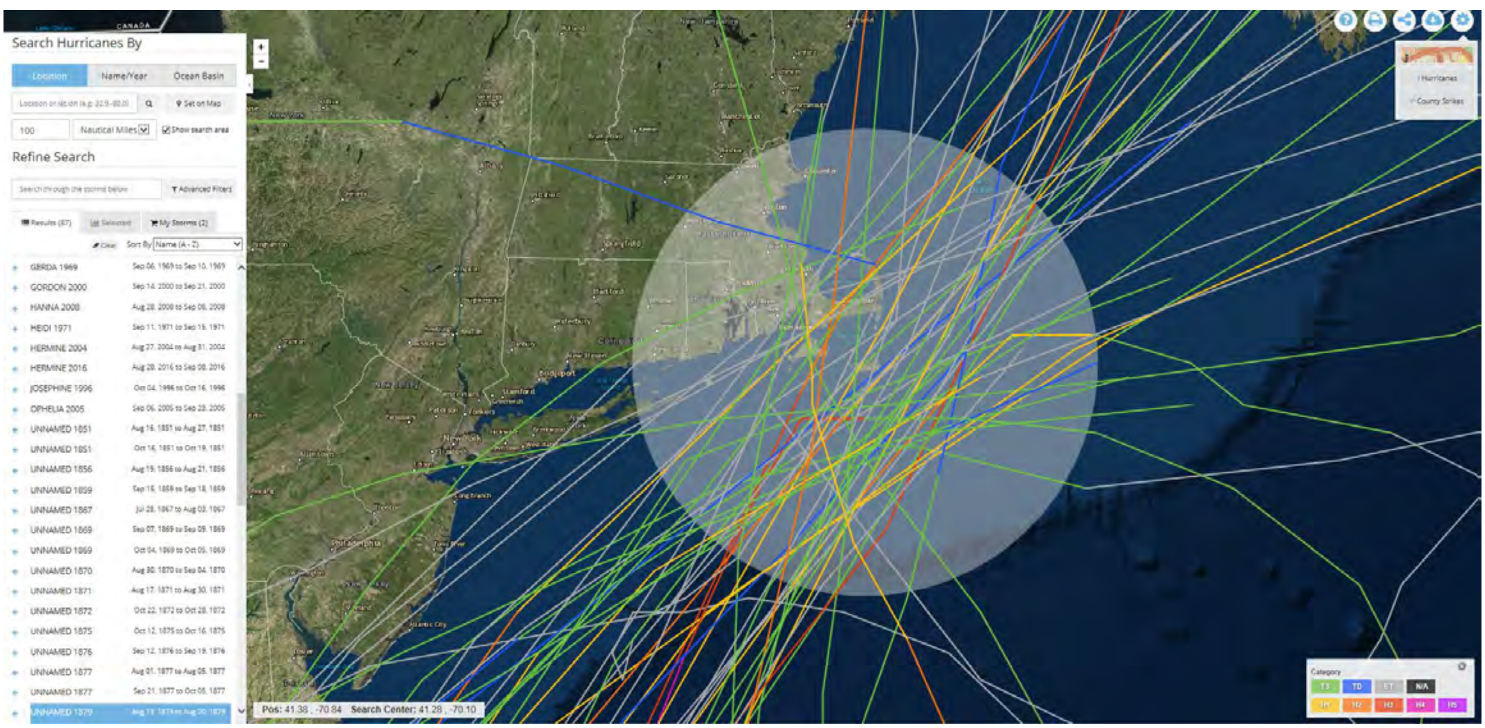


Figure 4: Tropical Cyclones (Hurricanes and Tropical Storms) passing within 100 nm of Nantucket
(Source: (Source: https://coast.noaa.gov/hurricanes/

Historic hurricane tracks which have passed within 100 nautical miles of Nantucket are presented in **Figure 5**. A total of 26 events (including tropical storms and hurricanes) occurred within this radius.

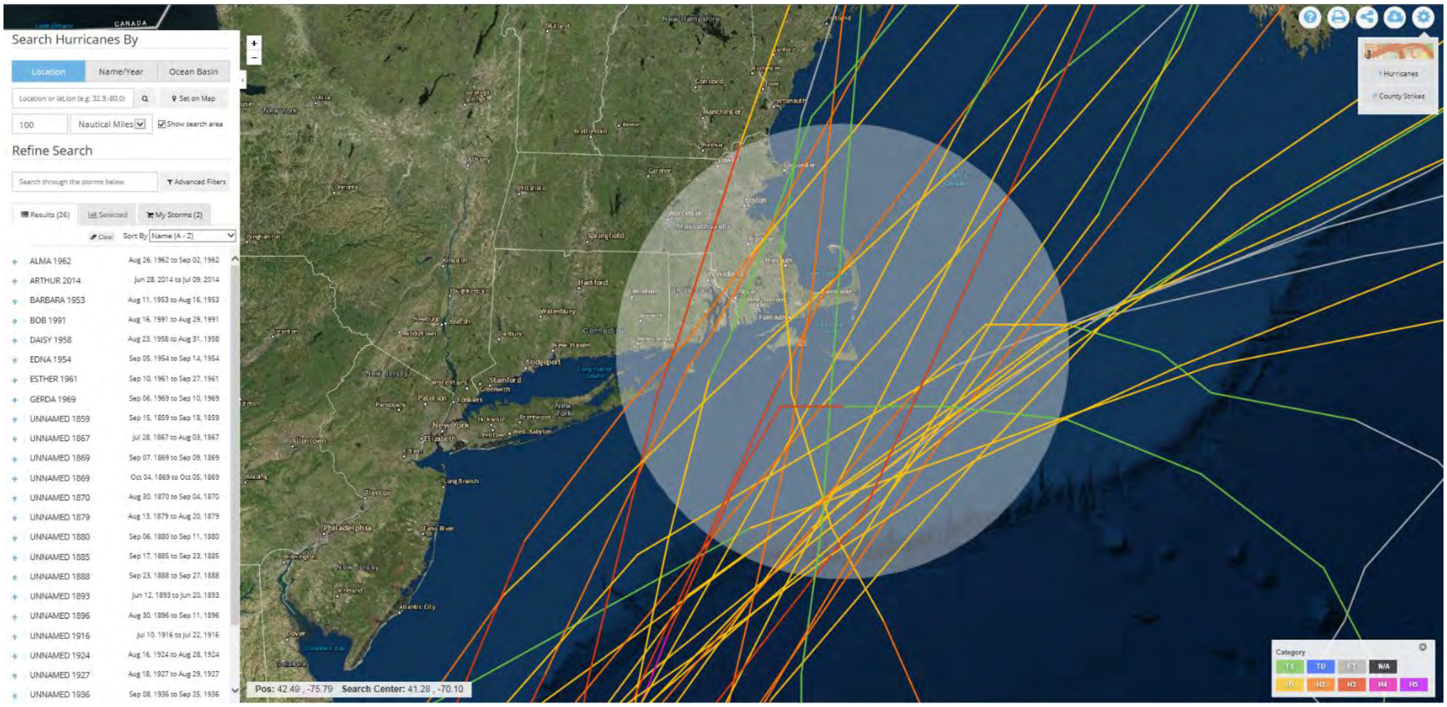


Figure 5: Hurricanes passing within 100 nm of Nantucket
(Source: (Source: https://coast.noaa.gov/hurricanes/

ALMA 1962	Aug 26, 1962 to Sep 02, 1962
ARTHUR 2014	Jun 28, 2014 to Jul 09, 2014
BARBARA 1953	Aug 11, 1953 to Aug 16, 1953
BOB 1991	Aug 16, 1991 to Aug 29, 1991
DAISY 1958	Aug 23, 1958 to Aug 31, 1958
EDNA 1954	Sep 05, 1954 to Sep 14, 1954
ESTHER 1961	Sep 10, 1961 to Sep 27, 1961
GERDA 1969	Sep 06, 1969 to Sep 10, 1969
UNNAMED 1859	Sep 15, 1859 to Sep 18, 1859
UNNAMED 1867	Jul 28, 1867 to Aug 03, 1867
UNNAMED 1869	Sep 07, 1869 to Sep 09, 1869
UNNAMED 1869	Oct 04, 1869 to Oct 05, 1869
UNNAMED 1870	Aug 30, 1870 to Sep 04, 1870
UNNAMED 1879	Aug 13, 1879 to Aug 20, 1879
UNNAMED 1880	Sep 06, 1880 to Sep 11, 1880
UNNAMED 1885	Sep 17, 1885 to Sep 23, 1885
UNNAMED 1888	Sep 23, 1888 to Sep 27, 1888
UNNAMED 1893	Jun 12, 1893 to Jun 20, 1893
UNNAMED 1896	Aug 30, 1896 to Sep 11, 1896
UNNAMED 1916	Jul 10, 1916 to Jul 22, 1916
UNNAMED 1924	Aug 16, 1924 to Aug 28, 1924
UNNAMED 1927	Aug 18, 1927 to Aug 29, 1927
UNNAMED 1936	Sep 08, 1936 to Sep 25, 1936
UNNAMED 1940	Aug 26, 1940 to Sep 03, 1940
UNNAMED 1944	Sep 09, 1944 to Sep 16, 1944
UNNAMED 1945	Jun 20, 1945 to Jul 04, 1945

Based on the historic hurricane track data an estimate of hurricane strikes centered at Nantucket for the period of +/-1850s to current is about 30 strikes. Nineteen (19) of these were category 1 hurricanes, 7 were Category 2 hurricanes; and 4 were major (Category 3) hurricanes. There were no Category 4 or 5 hurricanes. **Figures 6** and **7** show greater than Category 2 and major hurricanes within 100 nm of Nantucket.

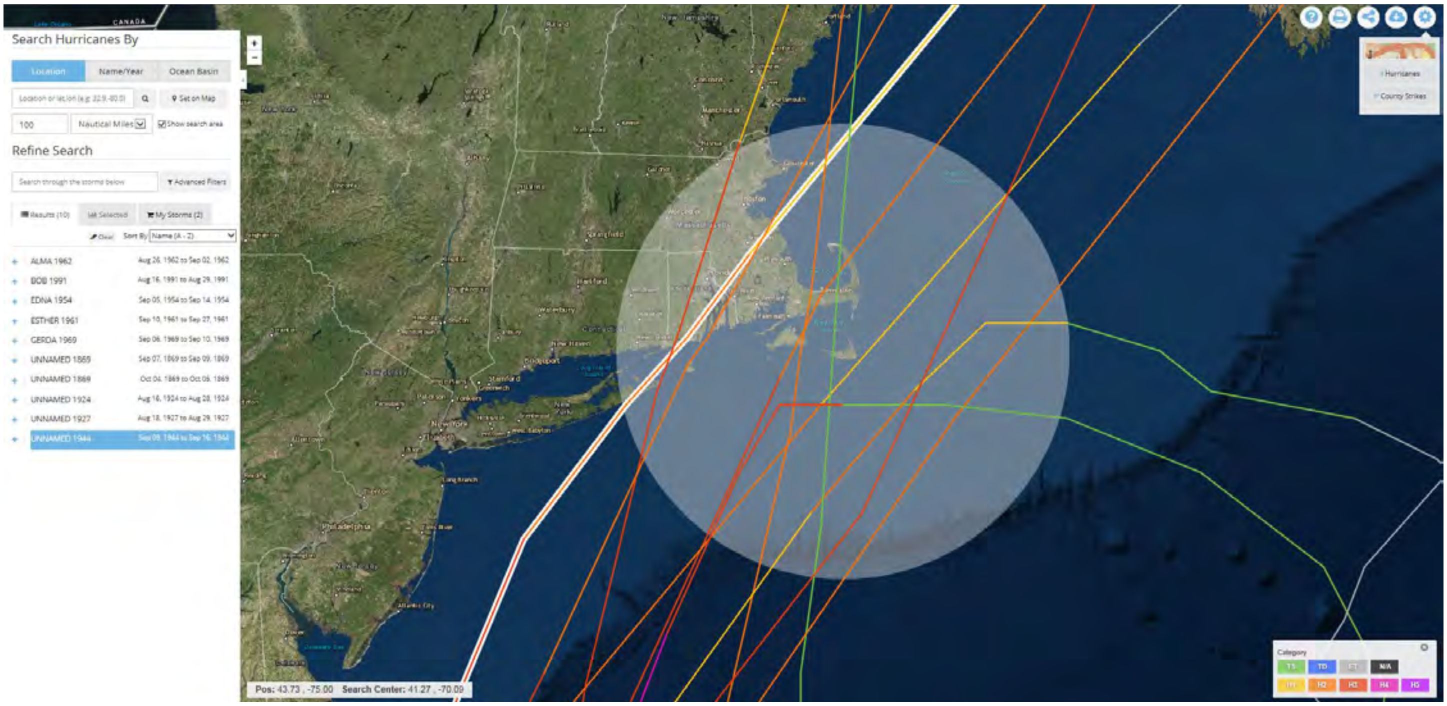


Figure 6: Hurricanes (Category 2 and greater) passing within 100 nm of Nantucket (Source: https://coast.noaa.gov/hurricanes/

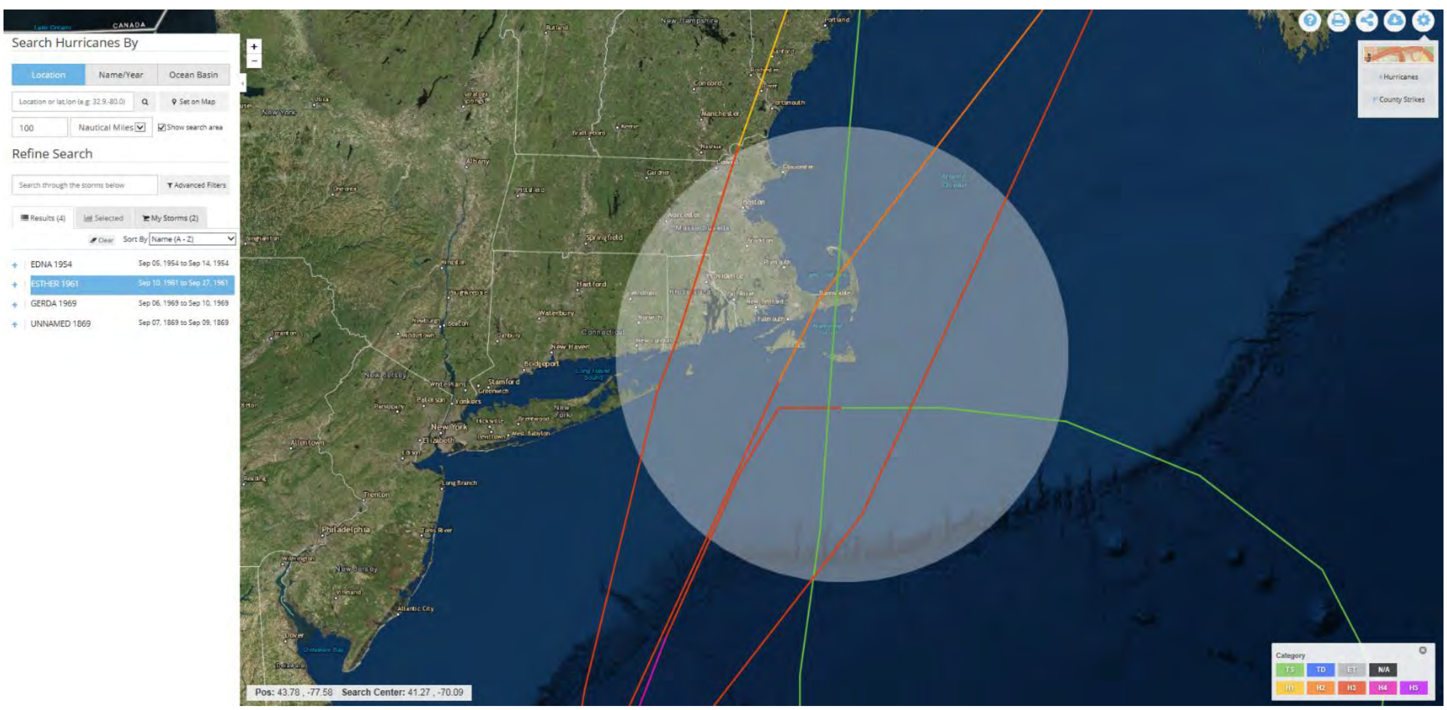


Figure 7: Hurricanes (Major) passing within 100 nm of Nantucket (Source: https://coast.noaa.gov/hurricanes/

The following figures show individual storm tracks and maximum sustained wind speeds along the track near Nantucket.

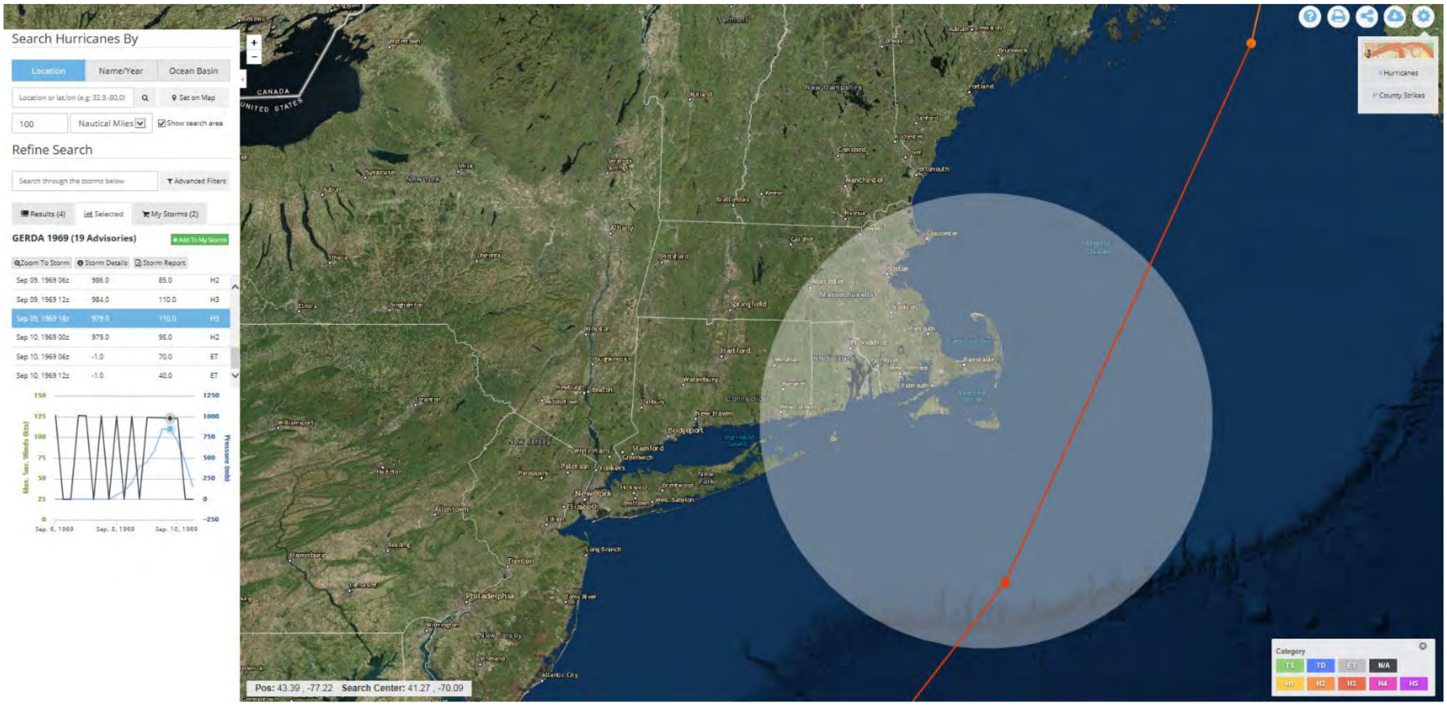


Figure 8: Hurricane Edna September 11, 1954; maximum sustained wind speed along storm track near Nantucket 125 kts (Source: https://coast.noaa.gov/hurricanes/

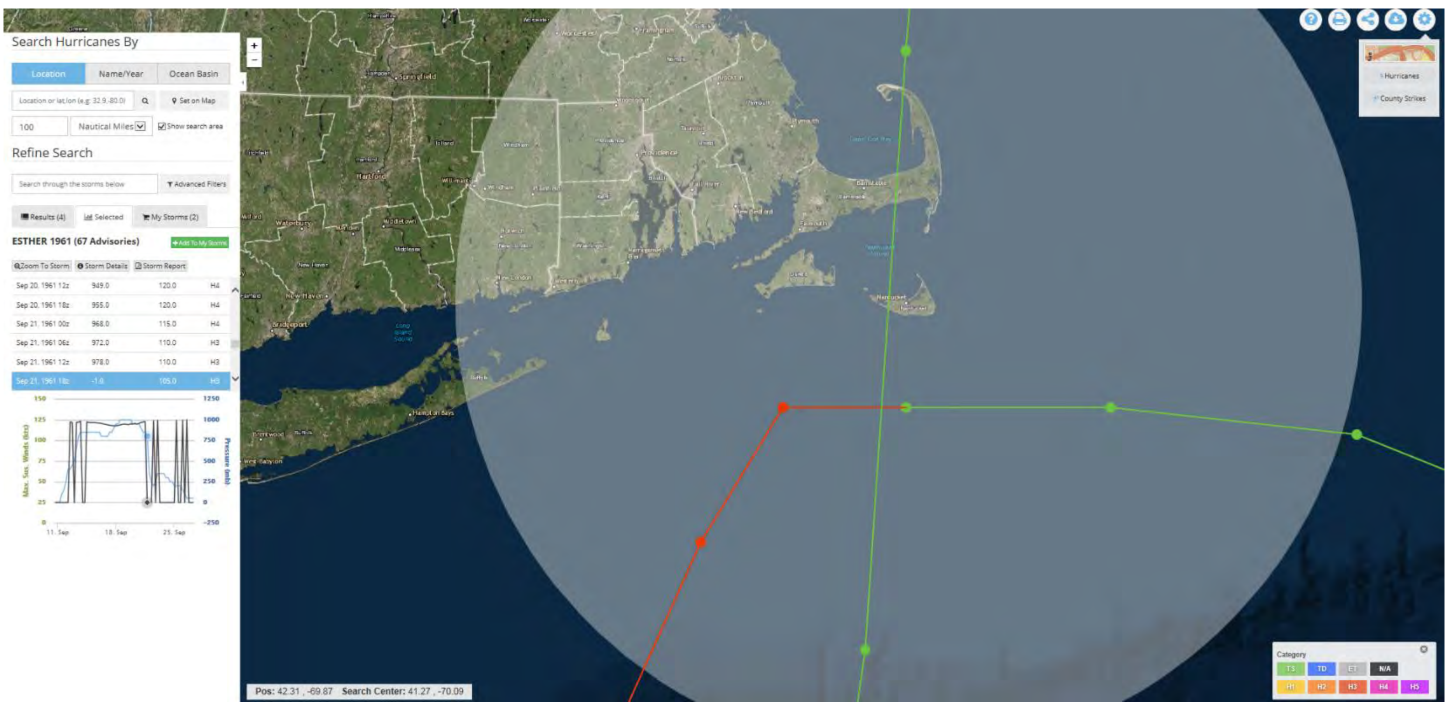


Figure 9: Hurricane Esther September 21, 1961; maximum sustained wind speed along storm track near Nantucket 105 kts (Source: https://coast.noaa.gov/hurricanes/

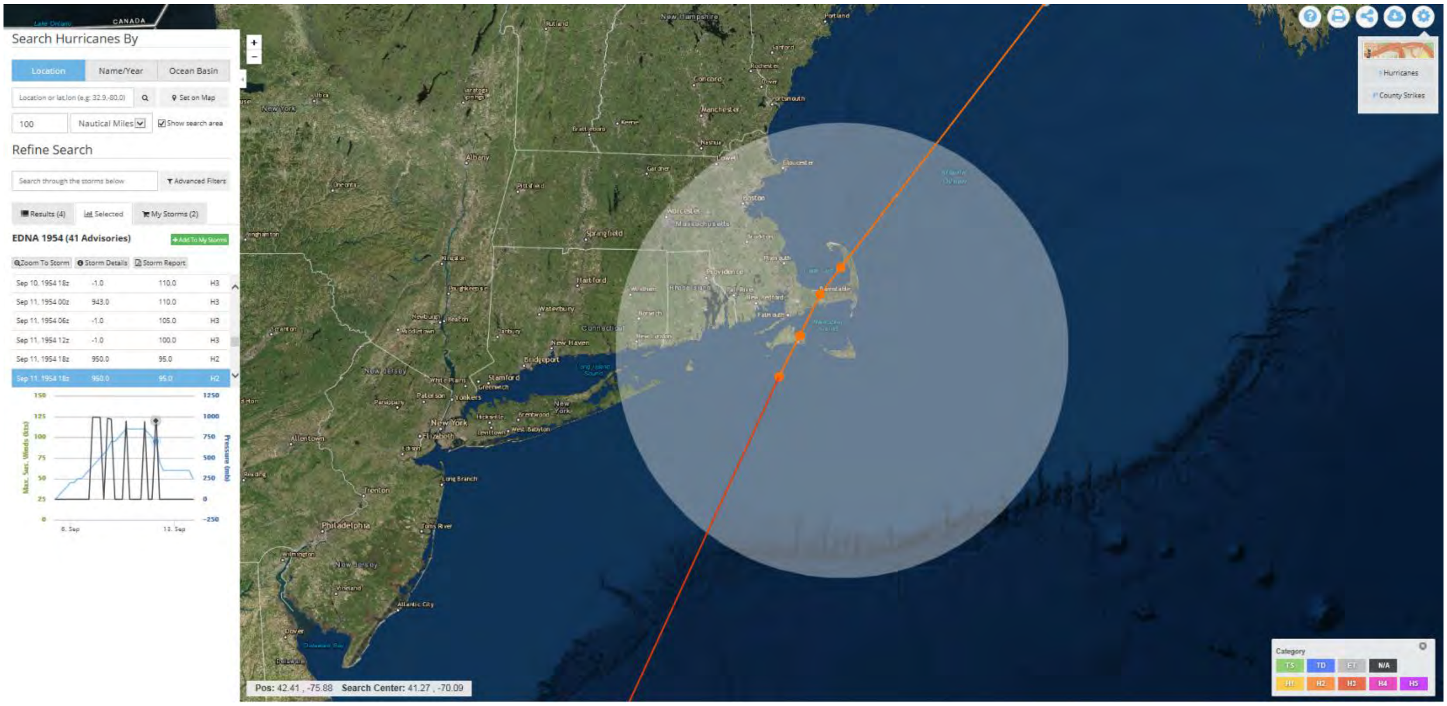


Figure 10: Hurricane Gerda September 9, 1969; maximum sustained wind speed along storm track near Nantucket 105 kts (Source: https://coast.noaa.gov/hurricanes/; Estimated maximum water level: 7.1 feet NOAA station data = 2.1 feet NAVD88

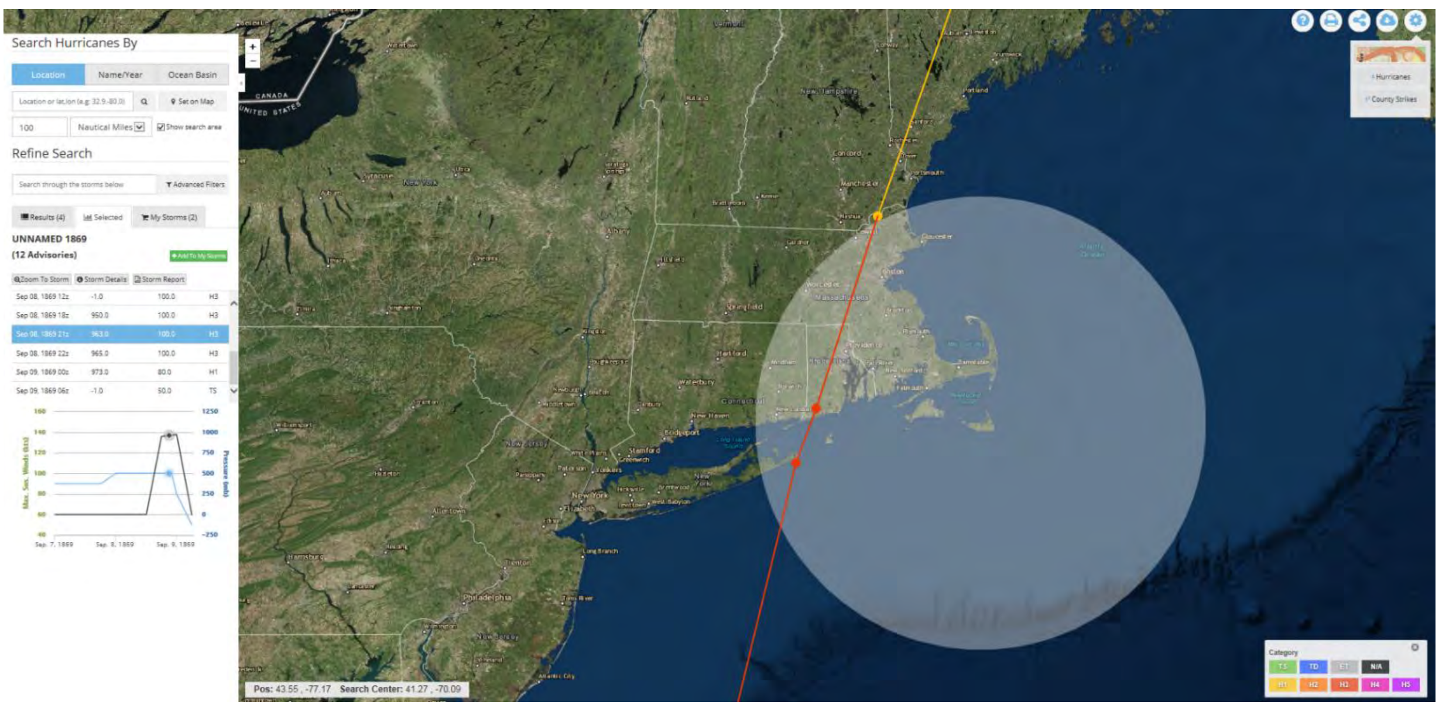


Figure 11: Unnamed Hurricane September 8, 1869; maximum sustained wind speed along storm track near Nantucket 100 kts (Source: https://coast.noaa.gov/hurricanes/

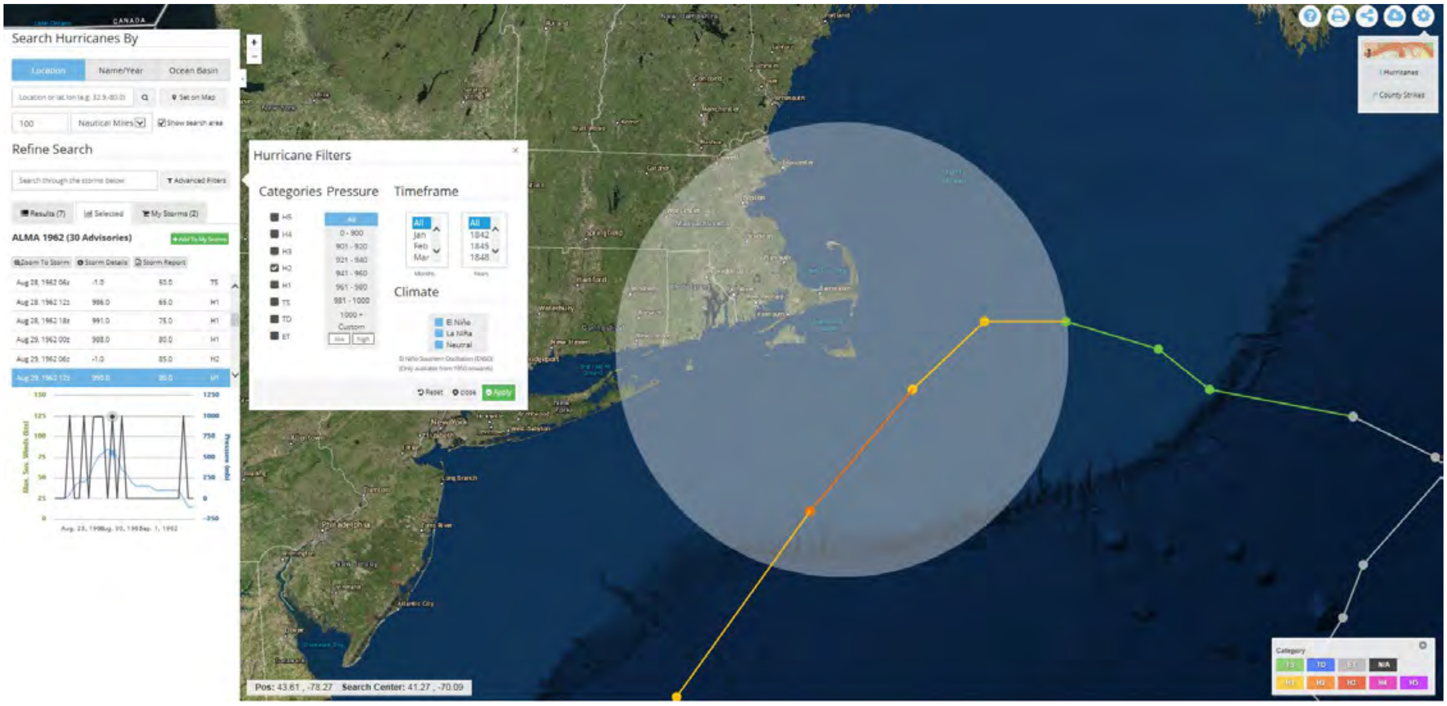


Figure 12: Hurricane Alma August 22, 1962; maximum sustained wind speed along storm track near Nantucket 80 kts (Source: https://coast.noaa.gov/hurricanes/

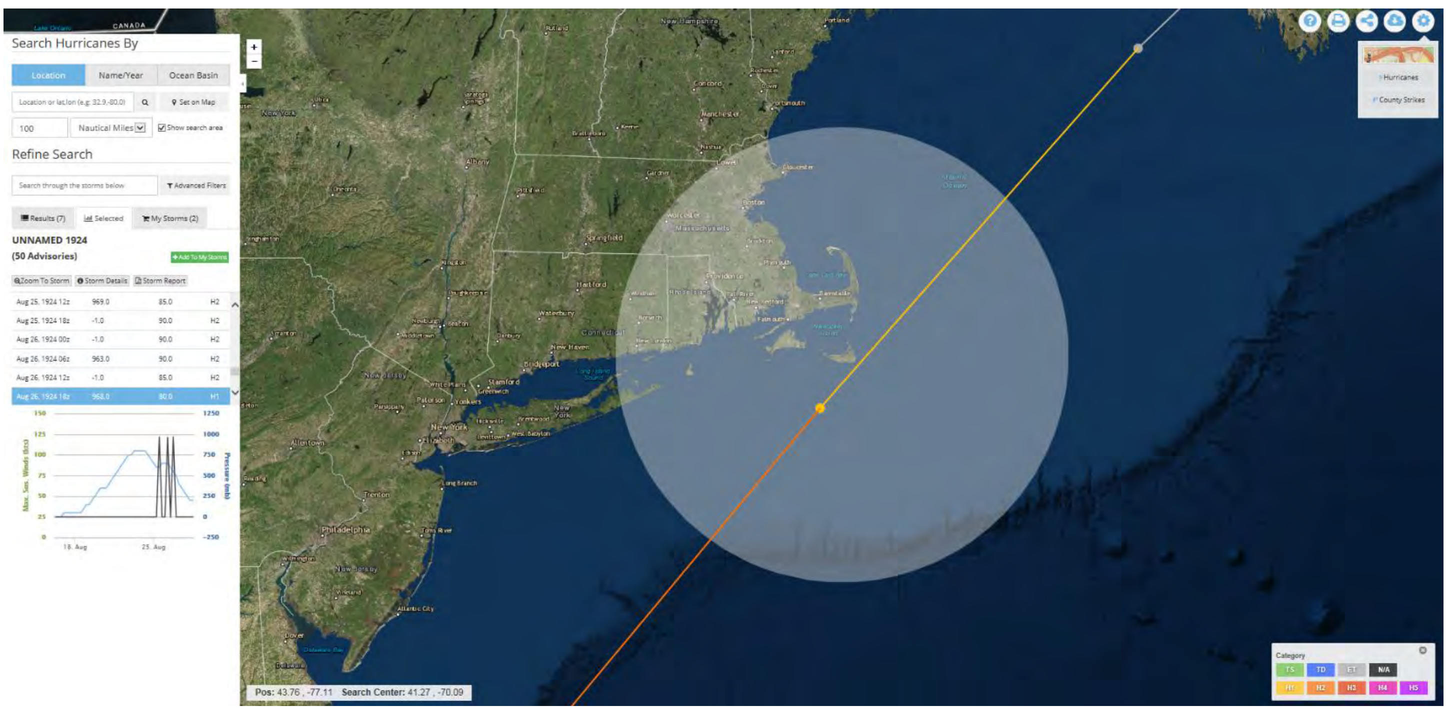


Figure 13: Unnamed Hurricane August 25, 1924; maximum sustained wind speed along storm track near Nantucket 80 kts (Source: https://coast.noaa.gov/hurricanes/

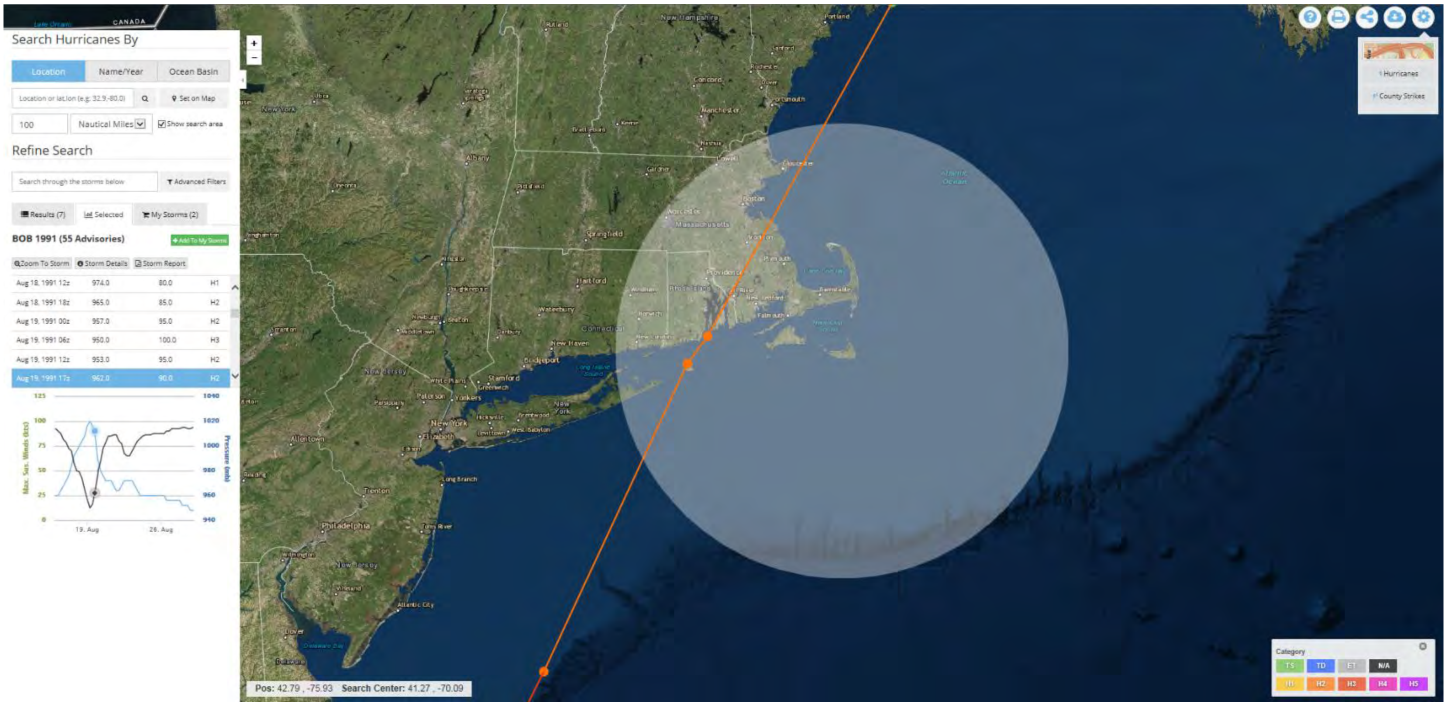


Figure 14: Hurricane Bob August 19, 1991; maximum sustained wind speed along storm track near Nantucket 90 kts (Source: https://coast.noaa.gov/hurricanes/

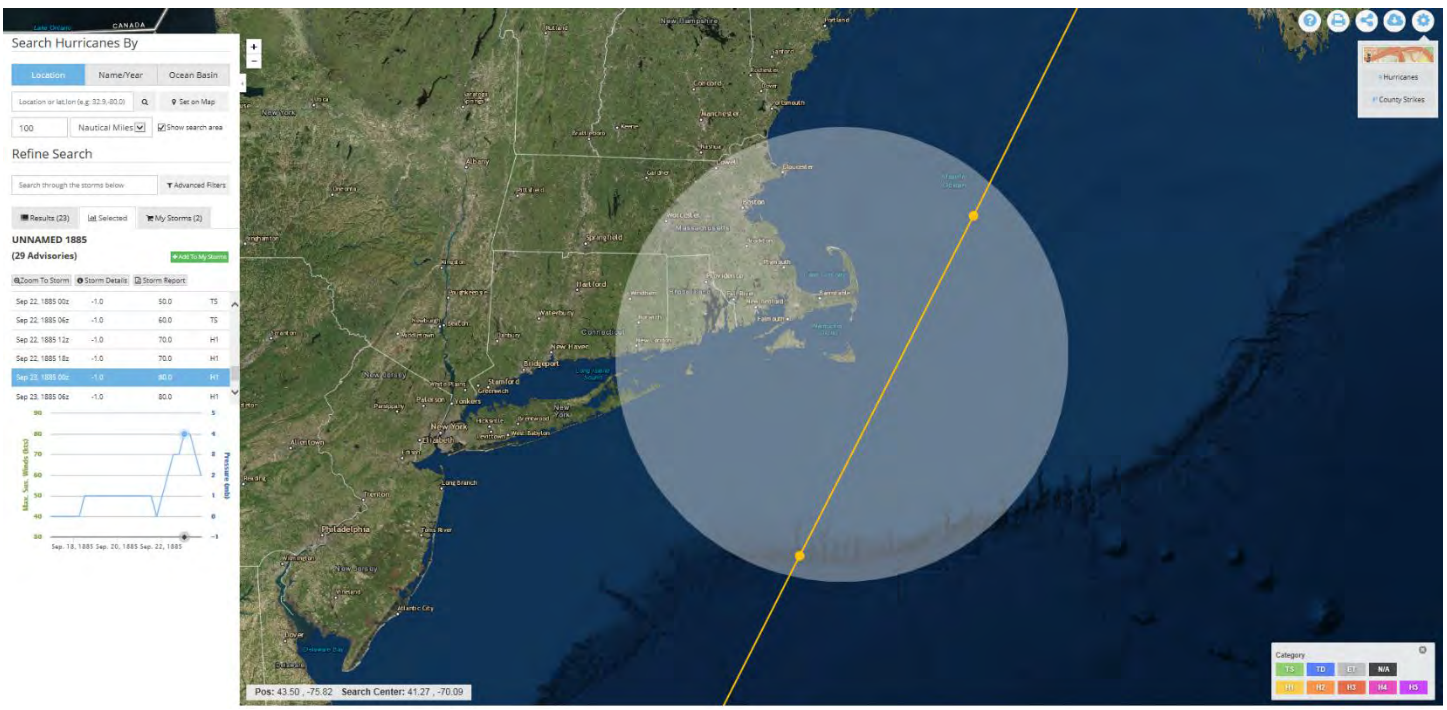


Figure 15: Unnamed Hurricane September 22, 1885; maximum sustained wind speed along storm track near Nantucket 80 kts (Source: https://coast.noaa.gov/hurricanes/

The following provides detailed description of Hurricane Gerda.

north of the center. Torrential rains in the mountains of Guatemala, Honduras, and British Honduras produced flooding of many rivers, with the Belize River rising to over 36 ft above normal.

It took the remnants of Francelia 3 days to cross Central America and the southern states of Mexico, prolonging torrential rains which had been falling in those sections for weeks. After emerging into the Pacific Ocean, the disturbance regained a circulation, and was eventually named tropical storm Glenda on September 7.

HURRICANE GERDA, AUGUST 21–SEPTEMBER 10

Hurricane Gerda had a comparatively short life for an early September hurricane. However, prior to development into a depression, the disturbance that probably generated the tropical cyclone can be traced across the Atlantic from the interior of northwestern Africa. The track from Africa was developed by following cloud masses on daily satellite pictures. Some of the cloud masses were organized, others disorganized.

On September 3, the disturbance merged with a degenerating midtropospheric cyclone to the north of Hispaniola and Puerto Rico. A larger cloud mass developed and continued toward the west-northwest at 10 mi hr⁻¹ until there were indications of a surface circulation forming in the western Bahamas on the 5th.

The weak tropical depression moved into southeastern Florida on the 6th, then drifted very slowly northward before emerging into the Atlantic near Cape Kennedy on the afternoon of the 7th. Thereafter, a northeasterly course with a steady fall in pressure began, and on the next morning a Navy reconnaissance aircraft found winds up to 50 kt and a sea-level pressure of 1000 mb.

The approach of a major trough in the westerlies produced rapid acceleration, and Gerda reached hurricane intensity on the afternoon of the 8th. The hurricane proceeded on a northeast to north-northeast course within 100 mi of the U.S. east coast, and eventually obtained a forward speed of 40 mi hr^{-1} as the center passed 50 mi off Cape Cod and moved inland over the extreme eastern tip of Maine by late afternoon and evening of September 9. The Nantucket lightship, about 75 mi southeast of Cape Cod, measured winds of 125 mi hr^{-1} and gusts to 140 mi hr^{-1}, as the center passed directly over the ship. Only gales were reported at Nantucket. The extremely high wind velocities, normally not produced by a hurricane with a central pressure of 979 mb, can be attributed, in part, to the rapid movement of the system and to the interaction with a strong trough in the westerlies.

Damage was minimal and confined mainly to marinas, downed trees, high powerlines, and to highways from the Cape Cod area to eastern Maine.

HURRICANE HOLLY, SEPTEMBER 9–21

The disturbance that became hurricane Holly could be identified as early as September 8, after it had moved off the African coast. Subsequently, it moved westward near 10° N. latitude until it reached 40° longitude, where it began a west-northwestward track.

By September 12, the disturbance had begun to show better organization on satellite pictures; it was a depression on the 13th, and Navy reconnaissance aircraft found a central pressure of 1000 mb on the following day. Steady but not rapid deepening occurred for the next 2 days. Hurricane intensity was obtained on the 15th, winds reached 75 kt, and the central pressure dropped to 984 mb (not shown in fig. 1) on the following day. Thereafter, the hurricane began to weaken steadily. On September 17, it was downgraded to a tropical storm, and to a depression on the 18th.

When Holly was downgraded to a depression, it was still 300 mi east of the Leeward Islands. It then moved west-southwestward and continued to weaken as it moved into the eastern Caribbean when it was barely perceptible from surface data. The last satellite pictures of an identifiable circulation showed weak but clear low-level banding with the cirrus canopy completely gone. By midday of the 21st, all traces of Holly had vanished.

When Holly was named, the environment seemed mildly favorable for development. The flow in the upper troposphere was anticyclonic, and there was little vertical shear. But from the beginning, analyses at high levels revealed no substantial outflow. As the system moved through the Lesser Antilles, an upper trough drifting eastward was becoming progressively better defined near 60° longitude. Holly moved under the cyclonic flow associated with the upper tropospheric trough and steadily deteriorated. It was then that the upper and lower level features drifted westward in tandem, inhibiting redevelopment of the storm.

HURRICANE INGA, SEPTEMBER 20–OCTOBER 14

Inga (longest lived Atlantic tropical cyclone of record) spent 25 days inside a relatively small circle (radius less than 700 mi) over the open Atlantic. It was born under adverse conditions, made a rather tight loop southeast of Bermuda, and then passed within 200 mi of Bermuda. It was along this northeastward track that the hurricane reached her greatest strength; winds were estimated to be 90 kt, and the sea-level pressure was reported to be 964 mb.

A cold Low to the east turned the hurricane toward the south; later, under the influence of a cold High to the north, Inga drifted westward and dissipated some 250 mi from where she first reached hurricane force.

TROPICAL STORM JENNY, OCTOBER 1–6

Jenny culminated a prolonged period of disturbed weather in the Gulf of Mexico that persisted for nearly a week. A cut-off Low in the upper troposphere triggered widespread showers and spawned two depressions prior to the formation of Jenny. The second depression moved into the Florida Panhandle on the same day that Jenny de-

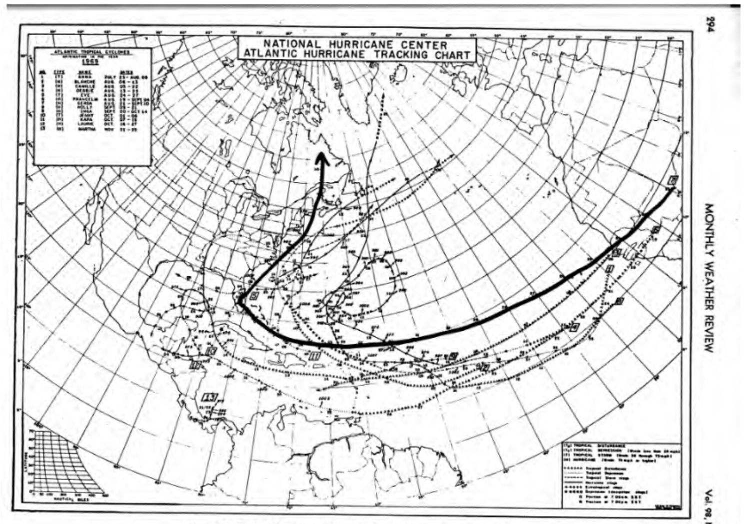


FIGURE 1.—Tracks of hurricanes and tropical storms in the North Atlantic in 1969.

Historical Nor'easters and Water Levels

Extratropical (nor'easters) storms are more frequent than tropical cyclones in the vicinity of Nantucket, often occurring multiple times per year. The top extreme water levels measured at the NOAA Nantucket tidal station, indicative of impactful storm events, are shown below. The storm characteristics for several of these storms are presented in the following figures.

Top Ten Highest Water Levels for long-term stations in feet above MHHW (as of 4/2018)

* --- Inferred Level & --- Last Recorded Level # --- High Water Mark

Station Number	Station Name	First	Second	Third	Fourth	Fifth	Sixth	Seventh	Eighth	Ninth	Tenth
8443970	Boston, MA	1/4/2018	2/7/1978	3/2/2018	1/2/1987	10/30/1991	1/25/1979	12/12/1992	12/29/1959	2/19/1972	1/3/2014
	(since 1921)	4.89	4.82	4.36	3.92	3.86	3.76	3.75	3.70	3.62	3.56
8447930	Woods Hole, MA	9/21/1938	8/31/1954	9/14/1944	8/19/1991	9/12/1960	10/29/2012	2/19/1972	11/30/1963	12/27/2012	12/2/1974
	(since 1932)	# 8.58	* 7.98	* 4.88	4.65	3.58	3.42	3.18	3.08	3.07	3.06
8449130	Nantucket Island, MA	10/30/1991	1/4/2018	1/27/2015	2/9/2013	3/3/2018	12/12/1992	1/3/2014	1/2/1987	1/30/2018	1/23/2005
	(since 1965)	4.29	3.72	3.64	3.23	3.16	3.09	3.00	2.77	2.75	2.63
8452660	Newport, RI	9/21/1938	8/31/1954	10/29/2012	8/19/1991	9/14/1944	1/9/1978	10/31/1991	2/7/1978	11/30/1963	12/2/1974
	(since 1930)	# 9.46	* 6.76	4.21	3.98	# 3.96	3.60	3.26	3.25	3.25	3.24
8454000	Providence, RI	9/21/1938	9/14/1944	8/19/1991	1/9/1978	9/12/1960	11/30/1963	10/29/2012	9/27/1985	1/23/1987	4/16/2007
	(since 1938)	# 12.67	* 5.87	5.15	4.91	4.77	4.67	4.35	4.31	4.28	4.07
8461490	New London, CT	9/21/1938	8/31/1954	10/30/2012	11/25/1950	9/14/1944	9/12/1960	11/7/1953	10/31/1991	8/28/2011	11/12/1968
	(since 1938)	# 7.53	* 6.53	4.89	4.53	* 4.03	3.83	3.73	3.42	3.39	3.33
8467150	Bridgeport, CT	10/30/2012	8/28/2011	12/11/1992	10/31/1991	10/25/1980	3/29/1984	9/27/1985	10/19/1996	11/12/1968	4/16/2007
	(since 1964)	5.72	4.72	4.72	4.06	3.67	3.29	3.27	3.21	3.20	3.19
8510560	Montauk, NY	8/31/1954	10/29/2012	2/6/1978	10/31/1991	11/25/1950	11/7/1953	11/12/1968	2/19/1972	12/11/1992	12/27/2010
	(since 1947)	5.91	4.53	4.22	3.80	3.71	3.41	3.31	3.24	3.21	3.07

NAVD88	5.82	5.25	5.17	4.76	4.69	4.62	4.53	4.30	4.28	4.16

Corrected for observed sea level rise at Nantucket (assuming 3.63 mm/yr [0.012 feet] historic rate):

NAVD88	6.1	5.3	5.2	4.8	4.7	4.9	4.6	4.7	4.3	4.3

The monthly minimum/maximum water levels by year are summarized in the following table (relative to station datum). To convert from station datum to NAVD88, subtract 5.04 feet from the station datum elevation. All of the top water level events as recorded at the NOAA Nantucket tide gage (period of record from 1965 to current), with the exception of the top observed water level which occurred during October, 1991. This storm (known as the Perfect Storm) was a hybrid tropical cyclone merged with an extratropical low pressure system.

Available, individual storm meteorological and water level time series data and surface weather maps are presented in **Figures 16** through **25**. Monthly water level data are plotted in Figures 26 (uncorrected) and 27 (corrected for sea level rise). GZA completed a statistical analysis of the monthly and annual peak data using Generalized Extreme Value statistics. The results are presented in **Figures 26** and **27**.

Historical Ocean Waves

Figure 28 shows wave statistics and the top 10 ocean wave events in the vicinity of Nantucket from the USACE Wave Information Studies dataset. Similar to observed water levels, within the period of record, the top wave events were due to the "Perfect Storm" and extratropical nor'easters.

Dec 20 2018 15:02 GMT

MAXIMUM, MINIMUM WATER LEVEL DATA
National Ocean Service (NOAA)

Station: 8449130
Name: Nantucket Island, MA
Type: Mixed
Note: [] Inferred Water Level Value

T.M.:
Units: Feet
Datum: StnDatum
Quality: Working

1965	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
Mean		4.44	4.35	4.47	4.42	4.50	4.51	4.43	4.45	4.59	4.62	4.46	
Maximum		7.30	7.00	7.10	6.80	7.30	7.40	7.10	7.00	7.30	7.20	7.00	
Max Day		13	7	13	5	3	1	26	24	23	23	13	
Max Time		00:00	00:00	00:00	00:00	00:00	00:00	00:00	00:00	00:00	00:00	00:00	
Minimum		1.50	2.10	2.30	2.10	2.00	2.20	2.20	2.20	2.00	2.20	2.10	
Min Day		23	13	5	3	28	2	30	28	19	14	10	
Min Time		00:00	00:00	00:00	00:00	00:00	00:00	00:00	00:00	00:00	00:00	00:00	

1966	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
Mean	4.61	4.37	4.37	4.36	4.38	[4.46]	[4.64]	[4.56]	4.68	4.45			
Maximum	7.70	7.40	7.50	7.20	6.70				7.40	6.90			
Max Day	8	5	5	2	7				15	11			
Max Time	00:00	00:00	00:00	00:00	00:00				00:00	00:00			
Minimum	1.40	1.90	1.90	2.00	1.80				2.20	1.90			
Min Day	4	8	9	7	5				14	14			
Min Time	00:00	00:00	00:00	00:00	00:00				00:00	00:00			

1967	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
Mean	4.41	4.34	4.37	4.65	[4.72]	[4.58]	4.55	4.49	4.62	4.57	4.61	[4.68]	
Maximum	7.40	7.30	7.20	8.60	8.30		6.90	6.80	6.80	7.30	7.60		
Max Day	28	23	7	29	25		12	7	2	6	4		
Max Time	00:00	00:00	00:00	00:00	00:00		00:00	00:00	00:00	00:00	00:00		
Minimum	2.00	1.40	1.90	1.90	2.00		2.20	2.40	2.20	2.20	1.90		
Min Day	8	24	2	26	24		19	16	9	7	29		
Min Time	00:00	00:00	00:00	00:00	00:00		00:00	00:00	00:00	00:00	00:00		

1968	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
Mean								4.55	4.58	4.57	4.77	4.43	
Maximum								7.00	6.90	7.60	8.50	7.80	
Max Day								11	27	25	12	21	
Max Time								00:00	00:00	00:00	00:00	00:00	
Minimum								2.40	2.30	2.40	2.00	2.10	
Min Day								6	5	27	20	17	
Min Time								00:00	00:00	00:00	00:00	00:00	

Dec 20 2018 15:02 GMT

MAXIMUM, MINIMUM WATER LEVEL DATA
National Ocean Service (NOAA)

Station: 8449130
Name: Nantucket Island, MA
Type: Mixed
Note: [] Inferred Water Level Value

T.M.: 8
Units: Feet
Datum: StnDatum
Quality: Working

1969	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
Mean	4.25	4.79	4.56		4.40	4.58	4.64	4.70	4.67	4.73	4.77	4.87	
Maximum	7.10	8.40	7.60		7.30	7.30	7.40	7.50	7.10	7.20	7.90	7.60	
Max Day	16	10	3		30	3	27	25	23	14	12	11	
Max Time	00:00	00:00	00:00		00:00	00:00	00:00	00:00	00:00	00:00	00:00	00:00	
Minimum	1.70	1.90	2.20		2.20	2.20	2.20	2.40	2.50	2.20	2.20	2.00	
Min Day	8	16	6		3	1	1	29	16	24	16	12	
Min Time	00:00	00:00	00:00		00:00	00:00	00:00	00:00	00:00	00:00	00:00	00:00	

1970	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
Mean	4.74	4.50	4.56	4.63	4.43	4.62	[4.62]	4.78	4.70	4.67	4.89	4.93	
Maximum	8.00	7.80	7.50	7.70	6.90	7.20		7.50	6.80	7.30	7.90	8.20	
Max Day	8	11	6	2	25	19		11	18	16	5	26	
Max Time	00:00	00:00	00:00	00:00	00:00	00:00		00:00	00:00	00:00	00:00	00:00	
Minimum	2.20	1.80	2.10	2.00	2.10	2.20		2.40	2.30	2.40	2.40	2.40	
Min Day	6	5	17	4	2	1		16	17	15	11	3	
Min Time	00:00	00:00	00:00	00:00	00:00	00:00		00:00	00:00	00:00	00:00	00:00	

1971	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
Mean	4.63	4.44	4.60	4.64	4.61	4.60	4.49	4.52	4.58	4.76	4.91	[4.52]	
Maximum	7.89	7.74	8.04	7.42	7.20	7.09	6.96	7.00	6.97	7.68	7.69		
Max Day	1	23	28	24	22	21	19	15	11	7	3		
Max Time	00:00	00:00	00:00	00:00	00:00	00:00	00:00	00:00	00:00	00:00	00:00		

Minimum	1.95	2.03	1.82	2.28	2.14	2.12	2.43	2.44	2.19	2.55	2.24		
Min Day	7	3	5	26	26	20	22	17	7	5	1		
Min Time	00:00	00:00	00:00	00:00	00:00	00:00	00:00	00:00	00:00	00:00	00:00		

1972	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
Mean	[4.40]	4.51	4.54	4.59	4.58	4.72	4.64	4.60	4.76	4.67	4.93	4.76	
Maximum		8.60	7.74	7.66	7.56	7.47	6.93	6.98	7.98	7.81	7.96	8.44	
Max Day		19	18	17	9	10	27	7	3	7	20	22	
Max Time		00:00	00:00	00:00	00:00	00:00	00:00	00:00	00:00	00:00	00:00	00:00	
Minimum		1.95	2.04	2.12	1.91	2.24	2.18	2.47	2.31	2.19	2.07	1.77	
Min Day		23	20	13	14	13	11	6	25	22	24	2	
Min Time		00:00	00:00	00:00	00:00	00:00	00:00	00:00	00:00	00:00	00:00	00:00	

Dec 20 2018 15:02 GMT

MAXIMUM, MINIMUM WATER LEVEL DATA
National Ocean Service (NOAA)

Station: 8449130
Name: Nantucket Island, MA
Type: Mixed
Note: [] Inferred Water Level Value

T.M.: 8
Units: Feet
Datum: StnDatum
Quality: Verified

1973	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
Mean	4.66	4.64	4.70	4.66	4.60	4.53	4.63	4.63	4.68	4.68	4.47	4.40	
Maximum	7.88	8.16	8.63	8.16	7.45	7.22	7.37	7.01	7.25	7.11	7.66	7.25	
Max Day	29	12	23	5	5	2	29	1	15	16	11	15	
Max Time	00:00	00:00	00:00	00:00	00:00	00:00	00:00	00:00	00:00	00:00	00:00	00:00	
Minimum	2.19	2.11	1.96	1.92	2.11	1.99	2.05	2.38	2.36	2.46	1.95	2.10	
Min Day	17	14	8	16	2	3	2	26	26	14	11	19	
Min Time	00:00	00:00	00:00	00:00	00:00	00:00	00:00	00:00	00:00	00:00	00:00	00:00	

1974	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
Mean	4.52	4.51	4.27	4.31	4.42	4.50	4.57	[4.45]	[4.69]	[4.45]	4.69	4.64	
Maximum	7.51	7.74	7.51	7.04	7.35	7.46	7.30				7.68	7.70	
Max Day	7	7	31	25	24	23	19				13	2	
Max Time	00:00	00:00	00:00	00:00	00:00	00:00	00:00				00:00	00:00	
Minimum	1.74	2.07	1.61	1.95	2.12	2.13	2.21				2.04	2.05	
Min Day	8	6	5	11	21	20	22				16	30	
Min Time	00:00	00:00	00:00	00:00	00:00	00:00	00:00				00:00	00:00	

1975	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
Mean	4.43	4.45	4.48	4.56	4.54	4.62	4.60	4.72	4.63	4.83	4.78	4.68	
Maximum	7.53	7.21	7.21	7.34	7.05	7.11	7.12	7.19	7.27	7.19	7.70	7.71	
Max Day	26	25	30	3	28	8	10	7	3	8	24	22	
Max Time	00:00	00:00	00:00	00:00	00:00	00:00	00:00	00:00	00:00	00:00	00:00	00:00	
Minimum	2.00	1.66	1.93	2.03	2.24	2.23	2.18	2.54	2.30	2.01	2.01	1.95	
Min Day	28	26	27	24	26	23	13	10	7	4	2	19	
Min Time	00:00	00:00	00:00	00:00	00:00	00:00	00:00	00:00	00:00	00:00	00:00	00:00	

1976	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
Mean	4.53	[4.30]	4.46	4.56	4.41	4.45	4.68	4.57	4.70	4.65	4.42	4.19	
Maximum	7.52	7.29	8.21	6.96	7.12	7.18	7.49	6.96	7.22	7.58	7.23	7.78	
Max Day	1	17	17	10	19	13	13	30	27	26	22	21	
Max Time	00:00	00:00	00:00	00:00	00:00	00:00	00:00	00:00	00:00	00:00	00:00	00:00	
Minimum	2.01	1.85	1.38	1.65	1.63	2.04	2.44	2.46	2.44	1.56	1.65	1.51	
Min Day	27	16	18	16	14	14	10	7	24	23	23	18	
Min Time	00:00	00:00	00:00	00:00	00:00	00:00	00:00	00:00	00:00	00:00	00:00	00:00	

Dec 20 2018 15:02 GMT

MAXIMUM, MINIMUM WATER LEVEL DATA
National Ocean Service (NOAA)

Station: 8449130
Name: Nantucket Island, MA
Type: Mixed
Note: [] Inferred Water Level Value

T.M.: 8
Units: Feet
Datum: StnDatum
Quality: Verified

1977	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
Mean	4.30	4.27	4.36	[4.24]	4.55	4.78	4.54	4.58	4.85	4.79	4.64	4.78	
Maximum	7.90	6.93	7.40	7.61	7.66	7.31	7.28	6.82	7.44	7.86	7.80	7.41	
Max Day	10	25	23	6	10	3	2	24	21	15	26	9	
Max Time	00:00	00:00	00:00	00:00	00:00	00:00	00:00	00:00	00:00	00:00	00:00	00:00	
Minimum	1.48	2.09	1.58	1.57	1.89	2.17	2.19	2.30	2.43	2.45	1.98	1.45	
Min Day	11	22	10	4	4	1	29	28	16	25	27	11	
Min Time	00:00	00:00	00:00	00:00	00:00	00:00	00:00	00:00	00:00	00:00	00:00	00:00	

1978	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
Mean	4.49	4.83	4.42	[4.63]	4.56	4.55	4.61	4.65	4.80	4.67	4.71	4.62	
Maximum	8.03	9.13	7.82		7.16	7.21	7.23	7.34	7.00	7.16	7.55	8.00	
Max Day	9	7	4		26	20	17	17	9	7	30	25	
Max Time	00:00	00:00	00:00		00:00	00:00	00:00	00:00	00:00	00:00	00:00	00:00	

Minimum	1.49	2.09	1.26		2.08	2.24	2.03	2.52	2.51	2.12	2.08	1.96	
Min Day	10	4	6		23	22	20	17	15	31	2	30	
Min Time	00:00	00:00	00:00		00:00	00:00	00:00	00:00	00:00	00:00	00:00	00:00	

1979	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
Mean	4.73	[4.40]			4.44			4.70		4.68	4.48		
Maximum	8.79				7.00			7.33		7.41	6.91		
Max Day	25				25			9		7	4		
Max Time	00:00				23:42			00:18		13:12	11:36		
Minimum	1.79				2.19			2.42		1.94	2.13		
Min Day	4				19			10		8	25		
Min Time	00:00				11:54			07:24		20:12	22:24		

1980	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
Mean										4.68	4.71	4.37	
Maximum										7.40	7.53	6.94	
Max Day										25	23	17	
Max Time										12:48	12:12	07:30	
Minimum										1.67	1.66	1.30	
Min Day										26	26	21	
Min Time										20:24	21:36	17:30	

Dec 20 2018 15:02 GMT

MAXIMUM, MINIMUM WATER LEVEL DATA
National Ocean Service (NOAA)

Station: 8449130
Name: Nantucket Island, MA
Type: Mixed
Note: [] Inferred Water Level Value

T.M.: 8
Units: Feet
Datum: StnDatum
Quality: Verified

1981	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
Mean	[4.20]	4.22	4.70	4.30	4.66	4.70	4.68	4.76	4.88	4.67	4.91	4.78	
Maximum		7.49	7.74	6.76	7.54	7.37	7.21	7.18	7.40	7.39	8.00	7.99	
Max Day		26	7	25	7	5	29	24	19	16	16	10	
Max Time		05:06	12:54	04:00	02:18	01:36	22:36	20:00	16:00	13:48	15:18	10:18	
Minimum		0.86	2.21	1.46	2.02	1.96	1.79	2.37	2.49	2.16	2.21	1.53	
Min Day		12	15	7	9	2	2	1	20	14	13	16	
Min Time		12:30	14:12	07:54	10:24	05:36	06:12	06:42	23:12	18:12	19:06	23:12	

1982	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
Mean	4.40	4.36	4.34	4.33	4.49	4.84	4.67	4.65	4.75	4.95	4.52	4.69	
Maximum	7.98	7.26	7.20	7.73	7.13	7.54	7.61	6.94	7.57	8.26	7.27	7.45	
Max Day	10	21	7	6	26	19	20	17	18	9	3	18	
Max Time	11:54	10:12	09:42	22:42	02:06	21:54	23:30	22:30	00:00	16:30	12:48	13:36	
Minimum	1.86	1.55	1.51	1.69	2.00	2.18	2.49	2.39	2.47	2.60	2.27	1.89	
Min Day	18	8	28	26	23	24	19	20	14	19	16	4	
Min Time	13:06	18:18	08:00	07:48	05:48	08:12	04:18	06:30	02:36	19:42	18:30	21:00	

1983	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
Mean	4.60	4.85	4.92	4.78	4.66	4.73	4.91	4.89	4.84	4.95	5.09	4.76	
Maximum	7.75	8.06	7.54	7.39	7.31	7.20	7.46	7.64	7.35	7.71	8.29	7.67	
Max Day	29	12	2	17	17	13	22	10	6	25	25	24	
Max Time	11:48	11:42	14:42	02:24	03:00	01:00	22:24	00:36	23:24	13:24	14:42	15:42	
Minimum	1.97	2.30	2.08	2.22	2.17	2.21	2.45	2.56	2.69	2.64	2.30	1.92	
Min Day	27	27	30	30	19	12	11	8	9	31	25	21	
Min Time	16:42	18:06	06:54	08:18	11:18	06:36	06:18	05:12	07:24	01:18	22:54	19:12	

1984	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
Mean	4.55	4.59	4.81	4.97	4.66	4.81	4.72	4.89	4.78	4.91	4.96	4.56	
Maximum	7.59	7.55	8.13	7.68	7.34	7.71	7.32	7.16	7.18	7.48	7.43	7.65	
Max Day	19	17	29	17	5	2	27	31	26	1	12	22	
Max Time	12:42	11:42	22:36	00:54	02:24	01:36	22:48	00:00	00:00	00:00	00:00	00:00	
Minimum	1.68	2.10	2.18	2.70	2.45	2.35	2.45	2.63	2.38	2.35	2.11	1.66	
Min Day	22	15	13	18	15	13	30	1	27	25	23	26	
Min Time	21:24	16:24	14:18	07:54	06:12	05:48	07:12	00:00	00:00	00:00	00:00	00:00	

Dec 20 2018 15:02 GMT

MAXIMUM, MINIMUM WATER LEVEL DATA
National Ocean Service (NOAA)

Station: 8449130
Name: Nantucket Island, MA
Type: Mixed
Note: [] Inferred Water Level Value

T.M.: 8
Units: Feet
Datum: StnDatum
Quality: Verified

1985	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
Mean	4.78	4.48	4.51	4.54	4.72	4.79	4.76	4.79	4.79	4.73	4.87	4.79	
Maximum	8.12	7.83	7.16	7.13	7.56	7.31	7.14	6.98	6.87	7.41	7.21	8.03	
Max Day	5	13	13	8	7	4	2	22	24	15	14	12	
Max Time	10:00	06:30	05:18	02:06	01:30	00:18	23:54	16:42	20:42	12:36	13:00	11:36	

Minimum	2.04	1.99	1.99	2.09	1.98	2.30	2.37	2.80	2.33	1.97	2.11	2.16
Min Day	9	18	16	7	5	3	1	3	18	17	13	15
Min Time	19:54	17:42	15:00	07:24	06:06	06:00	04:54	07:54	20:48	20:36	18:24	21:00

1986	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
Mean	4.40	4.72	4.38	4.85	4.83	4.73	4.88	4.77	4.72	4.90	4.69	4.64	
Maximum	7.44	7.35	7.06	7.78	7.78	7.74	7.66	8.00	6.82	7.34	7.74	8.31	
Max Day	27	5	2	24	12	23	20	18	13	5	19	31	
Max Time	12:42	08:18	04:24	23:48	01:48	00:06	23:00	23:06	19:30	01:30	13:00	11:18	
Minimum	1.62	2.21	1.89	2.10	2.33	2.31	2.48	2.74	2.60	2.57	2.25	1.78	
Min Day	9	9	29	1	25	24	23	14	15	8	1	5	
Min Time	17:12	18:42	08:18	11:18	07:06	07:48	07:18	00:12	03:00	21:42	17:06	21:18	

1987	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
Mean	4.89	4.59	4.86	4.79	4.62	4.79	4.84	4.84	4.78	4.77	4.73	4.99	
Maximum	9.34	7.54	7.46	7.54	7.00	7.35	7.60	7.60	7.01	7.46	8.16	7.69	
Max Day	2	9	23	30	17	14	10	10	30	1	12	1	
Max Time	13:24	22:12	05:36	00:30	02:36	01:24	23:06	00:06	17:30	18:24	04:24	08:36	
Minimum	2.34	2.19	2.25	2.30	1.93	2.30	2.63	2.68	2.33	2.09	2.12	2.39	
Min Day	25	28	6	19	14	13	12	8	7	9	24	24	
Min Time	13:54	18:30	11:00	10:18	06:24	07:00	06:36	04:36	05:00	19:30	20:36	21:06	

1988	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
Mean	4.40	4.54	4.41	4.96	4.63	4.83	4.66	4.74	4.73	4.81	4.70	4.61	
Maximum	7.64	7.68	7.54	7.51	7.11	7.57	7.51	7.36	7.17	7.45	7.40	7.53	
Max Day	26	16	15	9	7	2	2	25	5	22	25	14	
Max Time	05:42	10:48	09:12	04:24	03:36	00:42	01:24	21:54	20:18	09:30	12:42	15:30	
Minimum	1.97	2.10	1.91	2.44	2.21	2.67	2.47	2.42	2.31	2.29	2.15	2.00	
Min Day	6	22	21	17	15	3	5	29	27	27	21	21	
Min Time	20:12	09:54	08:24	06:18	05:24	08:06	10:18	19:18	19:06	19:36	16:06	16:36	

Dec 20 2018 15:02 GMT

MAXIMUM, MINIMUM WATER LEVEL DATA
National Ocean Service (NOAA)

Station: 8449130
Name: Nantucket Island, MA
Type: Mixed
Note: [] Inferred Water Level Value

T.M.: 8
Units: Feet
Datum: StnDatum
Quality:

1989	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
Mean	4.52	4.45	4.32	4.41	4.55	4.73	4.72	4.81	4.73	4.78	4.80	4.50	
Maximum	7.85	7.42	6.85	6.95	7.16	7.28	7.12	7.26	7.14	7.70	7.67	7.48	
Max Day	4	25	10	8	7	2	2	23	17	18	16	13	
Max Time	09:06	02:30	01:42	01:54	01:12	22:42	23:30	16:48	13:00	14:18	14:12	12:12	
Minimum	1.78	1.84	2.13	1.71	1.77	2.44	2.55	2.70	2.59	2.30	2.03	2.05	
Min Day	11	9	9	10	5	3	1	19	19	15	13	12	
Min Time	20:36	20:06	06:42	09:24	05:24	05:06	04:06	07:06	20:54	18:00	17:54	17:30	

1990	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
Mean	4.40	4.43	4.25	4.35	4.72	4.72	4.73	4.81	4.84	4.87	4.85	4.51	
Maximum	7.83	7.66	6.97	7.12	7.61	7.71	7.40	7.05	7.21	7.80	8.14	8.17	
Max Day	10	24	31	4	24	24	21	19	15	26	6	4	
Max Time	10:54	11:48	03:18	07:36	23:36	00:30	23:12	23:36	21:00	17:06	13:54	13:18	
Minimum	1.89	2.00	1.75	1.96	2.25	2.50	2.54	2.77	2.82	2.30	2.37	2.01	
Min Day	1	27	29	27	26	26	20	18	9	7	29	30	
Min Time	21:54	06:54	07:42	07:24	07:18	08:42	03:48	03:36	21:06	19:54	15:12	16:24	

1991	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
Mean	4.62	4.55	4.92	4.61	4.71	4.94	4.88	4.77	4.76	4.99	4.85	4.78	
Maximum	7.32	7.53	7.73	7.43	7.51	7.89	7.56	7.31	7.15	10.87	8.05	8.01	
Max Day	30	15	19	21	14	13	14	11	6	30	24	3	
Max Time	12:00	12:12	01:36	05:12	23:54	00:06	01:42	00:12	22:18	17:30	13:18	09:36	
Minimum	1.83	1.66	2.35	2.16	2.34	2.53	2.58	2.66	2.49	2.51	1.89	2.18	
Min Day	31	1	31	14	20	12	12	7	30	9	25	5	
Min Time	19:12	19:36	06:54	05:00	11:12	05:18	06:00	02:36	23:00	19:00	20:54	17:30	

1992	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
Mean	4.80	4.84	4.68	4.69	4.66	4.89	4.91	4.77	4.72	4.88	4.75	4.88	
Maximum	7.54	7.86	7.60	6.94	7.18	7.50	7.71	7.30	7.24	7.68	7.79	9.67	
Max Day	5	16	23	18	5	2	2	29	29	25	24	12	
Max Time	12:36	09:36	03:24	00:30	01:18	00:00	00:24	00:30	14:00	11:06	11:00	13:00	
Minimum	2.03	2.16	2.13	2.14	2.14	2.38	2.46	2.50	2.38	2.48	2.37	2.17	
Min Day	19	17	18	16	16	4	31	2	26	27	16	27	
Min Time	17:18	17:06	05:12	05:00	05:42	08:12	06:42	08:24	17:24	19:06	22:24	20:36	

Dec 20 2018 15:02 GMT

MAXIMUM, MINIMUM WATER LEVEL DATA
National Ocean Service (NOAA)

Station: 8449130

T.M.: 0 W

Name: Nantucket Island, MA
Type: Mixed
Note: [] Inferred Water Level Value

Units: Feet
Datum: StnDatum
Quality: Verified

1993	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
Mean	4.66	4.91	4.60	4.95	4.87	4.86	4.95	4.88	4.89	4.83	4.65	4.98	
Maximum	7.91	7.88	8.45	7.54	7.27	7.47	7.29	7.33	7.42	7.49	7.31	8.68	
Max Day	14	2	14	11	7	1	21	21	18	18	15	16	
Max Time	04:24	07:36	03:54	03:24	00:18	21:30	00:48	14:48	13:24	14:12	12:42	13:48	
Minimum	2.18	2.11	1.61	2.18	1.97	2.47	2.72	2.82	2.52	2.28	2.09	1.89	
Min Day	11	10	14	9	5	3	1	18	15	16	14	27	
Min Time	20:18	08:18	23:30	07:54	05:00	04:48	03:36	05:42	16:24	18:36	18:24	17:06	

1994	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
Mean	[4.31]	[4.48]	4.59	4.28	4.77	4.59	4.67	4.71	4.90	4.85	4.62	4.69	
Maximum			7.89	7.16	7.83	7.43	7.01	6.94	7.83	7.01	7.39	7.66	
Max Day			4	27	27	25	20	6	5	10	6	24	
Max Time			09:48	05:24	06:06	06:00	02:06	04:18	16:36	21:12	19:00	08:12	
Minimum			1.57	1.63	2.30	2.35	2.37	2.51	2.65	2.09	1.75	1.77	
Min Day			31	29	30	21	23	17	9	8	8	2	
Min Time			13:54	13:36	15:18	08:36	10:54	07:06	00:48	00:30	02:12	22:06	

1995	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
Mean	4.57	4.50	4.55	4.54	4.84	4.63	4.76	4.93	4.86	4.89	4.96	4.96	
Maximum	7.75	7.49	7.27	7.18	7.62	7.62	7.26	7.33	7.21	7.71	7.87	8.81	
Max Day	2	21	23	20	19	14	12	7	2	28	22	20	
Max Time	16:48	09:18	09:48	08:30	08:18	05:12	04:00	00:48	22:30	19:48	15:54	14:48	
Minimum	1.76	2.07	2.18	2.21	2.44	1.89	2.30	2.53	2.56	2.54	2.42	2.59	
Min Day	4	25	20	18	17	16	13	9	12	31	23	21	
Min Time	00:30	19:42	13:06	13:00	12:42	13:18	11:18	09:06	00:36	04:12	23:18	22:06	

1996	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
Mean	4.89	4.70	4.63	4.88	4.76	4.76	4.88	4.81	5.31	5.13	5.02	4.94	
Maximum	8.39	8.12	7.44	8.08	7.14	7.13	7.72	7.32	8.27	7.71	7.47	7.75	
Max Day	8	17	21	10	30	4	4	1	2	20	18	14	
Max Time	18:36	15:06	06:00	09:36	02:12	06:30	07:00	05:48	08:54	22:54	22:42	19:30	
Minimum	2.10	1.87	1.62	2.55	2.01	2.17	2.48	2.63	2.45	2.65	2.37	2.10	
Min Day	23	19	4	22	7	2	29	31	26	26	14	20	
Min Time	00:24	23:06	22:36	14:00	13:42	11:00	09:18	00:00	21:48	22:30	00:30	19:36	

Dec 20 2018 15:02 GMT

MAXIMUM, MINIMUM WATER LEVEL DATA
National Ocean Service (NOAA)

Station: 8449130
Name: Nantucket Island, MA
Type: Mixed
Note: [] Inferred Water Level Value

T.M.: 8 W
Units: Feet
Datum: StnDatum
Quality: Verified

1997	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
Mean	4.82	4.66	4.78	5.14	4.78	4.96	4.86	4.90	4.95	5.02	5.08	4.95	
Maximum	8.59	7.53	7.75	8.44	7.30	7.52	7.45	7.27	7.18	8.18	8.02	8.22	
Max Day	10	9	6	19	10	5	25	18	20	20	15	1	
Max Time	17:18	18:06	14:12	13:30	07:12	04:36	21:30	04:00	19:42	20:00	16:42	17:30	
Minimum	2.13	2.32	1.96	2.38	2.29	2.70	2.46	2.64	2.74	2.70	2.35	2.38	
Min Day	13	6	7	8	29	3	21	20	22	17	13	14	
Min Time	01:36	21:42	21:18	11:24	16:30	09:06	11:24	11:48	02:48	23:36	21:36	23:30	

1998	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
Mean	5.03	5.22	4.79	5.01	5.06	5.01	4.96	4.83	5.02	4.90	4.81	4.71	
Maximum	8.58	8.47	7.71	7.50	7.60	7.31	7.28	7.08	7.47	7.58	7.57	8.11	
Max Day	29	25	22	2	26	27	12	19	9	11	6	30	
Max Time	17:06	15:12	11:36	08:42	04:42	07:06	06:18	02:24	19:06	21:42	18:24	14:00	
Minimum	2.09	2.85	2.06	2.07	2.57	2.57	2.83	2.67	2.86	2.34	2.45	1.99	
Min Day	3	11	26	29	27	24	15	10	6	6	8	31	
Min Time	01:48	23:12	21:06	13:00	11:54	10:42	15:06	12:06	10:18	23:00	01:36	21:24	

1999	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
Mean	4.52	4.93	4.73	4.89	4.78	4.72	4.92	4.96	4.90	4.84	4.74	4.75	
Maximum	7.30	7.71	7.58	7.80	7.07	7.40	7.56	7.49	7.25	7.71	7.34	7.94	
Max Day	29	25	15	17	20	15	11	9	30	23	27	1	
Max Time	14:54	13:06	15:18	05:12	08:42	05:36	02:30	02:24	20:30	15:12	20:06	23:24	
Minimum	1.56	2.29	2.21	2.30	2.02	2.18	2.45	2.71	2.58	2.25	1.88	2.05	
Min Day	2	24	21	19	17	13	12	11	26	30	23	22	
Min Time	23:12	17:48	13:30	13:18	12:12	10:00	09:48	10:24	23:24	02:48	22:48	22:24	

2000	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
Mean	[4.55]	4.34	4.71	4.73	4.85	4.78	4.95	4.88	4.90	4.89	5.10	4.57	
Maximum		7.55	7.29	7.10	7.59	7.87	7.57	7.38	7.68	7.59	7.61	7.91	
Max Day		19	17	9	10	7	3	1	27	28	11	12	
Max Time		16:54	15:06	08:24	09:48	08:30	05:30	05:24	03:54	17:36	16:06	17:42	
Minimum		1.85	2.25	2.06	2.06	2.20	2.42	2.50	2.80	2.64	2.40	1.88	
Min Day		17	16	13	4	4	3	1	1	18	17	13	
Min Time		21:12	20:00	18:42	10:48	12:12	11:48	11:36	00:24	02:00	02:42	00:06	

Dec 20 2018 15:02 GMT

MAXIMUM, MINIMUM WATER LEVEL DATA
National Ocean Service (NOAA)

Station: 8449130
Name: Nantucket Island, MA
Type: Mixed
Note: [] Inferred Water Level Value

T.M.: 8 W
Units: Feet
Datum: StnDatum
Quality: Verified

2001	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
Mean	4.80	4.49	4.88	4.67	4.80	4.80	4.92	4.88	5.01	4.95	4.83	4.92	
Maximum	7.97	7.14	9.11	7.18	7.09	7.22	7.39	7.40	7.29	7.39	7.35	7.93	
Max Day	21	9	7	2	29	23	22	20	19	17	5	18	
Max Time	15:12	17:54	13:54	11:12	09:48	05:48	05:36	05:18	06:00	05:00	19:36	19:24	
Minimum	2.15	1.17	1.97	2.25	2.13	2.47	2.49	2.57	2.79	2.26	2.27	2.47	
Min Day	12	12	12	8	8	25	22	19	17	19	13	5	
Min Time	00:24	01:42	12:54	10:54	11:30	13:54	11:54	10:30	10:12	00:06	21:12	01:36	

2002	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
Mean	4.68	4.88	4.39	4.58	4.67	4.81	4.91	4.90	4.98	5.00	4.90	4.92	
Maximum	8.51	7.81	6.93	8.15	7.29	7.48	7.22	7.20	8.24	7.61	8.75	8.07	
Max Day	13	5	27	26	25	15	20	7	11	17	6	25	
Max Time	16:54	11:18	15:30	05:00	03:24	07:48	01:00	03:06	20:42	01:42	17:48	22:00	
Minimum	1.96	2.47	1.78	1.91	2.25	2.25	2.69	2.65	2.60	2.52	2.00	1.83	
Min Day	3	3	1	27	27	22	23	11	9	10	25	4	
Min Time	01:30	02:48	00:00	10:48	11:24	08:30	10:06	12:30	12:06	01:12	02:06	23:00	

2003	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
Mean	4.80	4.38	4.65	4.71	4.83	4.99	4.91	4.92	4.97	4.92	4.88	4.89	
Maximum	8.71	7.48	7.43	7.19	7.17	7.72	7.66	7.14	7.75	7.83	7.76	8.37	
Max Day	4	23	22	22	15	15	12	10	28	29	24	7	
Max Time	17:54	10:12	07:42	09:18	03:30	04:54	02:48	02:48	18:18	19:54	16:36	14:36	
Minimum	1.83	1.86	2.25	2.04	1.97	2.25	2.53	2.77	2.81	2.16	2.08	2.11	
Min Day	22	24	4	18	17	17	14	11	30	31	30	23	
Min Time	13:00	17:18	11:48	11:48	11:30	13:12	11:18	10:00	01:36	03:18	03:54	22:54	

2004	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
Mean	4.73	4.61	[4.63]	4.62	4.67	4.86	[4.91]	4.89	4.95	5.28	5.01	[4.89]	
Maximum	7.55	7.96	7.62	7.39	7.20	7.68		7.47	7.62	7.75	7.98		
Max Day	18	19	17	9	7	3		1	29	24	13		
Max Time	14:00	15:42	14:00	07:36	06:18	04:12		04:48	17:18	01:18	17:00		
Minimum	2.31	2.06	2.18	2.27	2.05	2.09		2.62	2.88	2.74	2.50		
Min Day	20	9	13	20	9	4		27	4	19	11		
Min Time	21:48	00:36	16:12	11:36	14:42	11:42		08:12	02:18	02:12	21:42		

Dec 20 2018 15:02 GMT

MAXIMUM, MINIMUM WATER LEVEL DATA
National Ocean Service (NOAA)

Station: 8449130
Name: Nantucket Island, MA
Type: Mixed
Note: [] Inferred Water Level Value

T.M.: 8 W
Units: Feet
Datum: StnDatum
Quality: Verified

2005	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
Mean	[4.88]	[4.88]	5.04	4.99	5.26	5.05	5.06	5.01	4.98	5.17	4.91	4.84	
Maximum			8.23	7.91	8.88	7.81	7.86	7.53	7.45	8.06	7.71	7.70	
Max Day			1	28	25	23	22	18	18	25	22	30	
Max Time			08:12	07:30	05:06	05:00	04:48	02:42	04:18	23:36	22:30	15:42	
Minimum			2.16	2.54	2.57	2.50	2.88	2.73	2.79	2.84	2.44	2.05	
Min Day			9	9	6	25	21	19	21	18	14	8	
Min Time			22:12	11:00	09:06	13:18	10:12	09:54	00:30	23:12	21:30	04:06	

2006	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
Mean	4.87	4.83	[4.79]	4.80	5.10	5.01	4.93	5.06	5.13	5.17	5.02	4.75	
Maximum	8.60	8.34		7.20	7.52	7.45	7.30	7.43	7.63	7.83	7.69	7.99	
Max Day	31	12		28	27	15	14	11	12	28	9	4	
Max Time	18:12	16:36		04:42	04:18	07:18	06:54	05:42	20:24	21:54	19:30	16:30	
Minimum	2.09	2.41		2.29	2.66	2.78	2.53	2.98	2.81	2.35	2.13	2.14	
Min Day	20	19		29	28	16	12	9	11	8	5	9	
Min Time	02:18	02:00		11:48	11:30	14:18	11:30	10:12	00:48	23:36	22:24	01:48	

2007	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
Mean	4.78	4.61	4.44	4.90	4.72	5.12	5.00	5.00	4.93	5.11	4.96	4.81	
Maximum	7.83	7.63	7.57	8.43	7.67	7.88	7.56	7.53	7.54	7.45	9.11	7.74	
Max Day	29	23	17	18	17	13	13	9	28	27	3	21	
Max Time	13:36	09:18	14:48	04:30	04:24	02:12	03:06	01:00	17:36	17:12	23:42	13:30	
Minimum	2.35	2.01	1.46	2.47	2.27	2.81	2.91	3.03	2.79	2.31	2.01	1.98	
Min Day	3	16	22	21	15	16	14	4	4	26	25	26	
Min Time	22:48	21:54	13:06	13:48	09:00	11:30	10:24	02:00	03:54	22:36	23:24	00:00	

2008	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
Mean	4.80	4.67	4.74	4.76	5.19	5.05	4.97	5.09	5.03	5.19	5.06	4.70	
Maximum	8.29	7.61	7.64	7.34	8.11	7.87	7.66	7.88	7.14	8.06	7.89	8.21	
Max Day	28	7	15	13	10	5	2	1	2	20	15	12	
Max Time	09:00	16:42	11:12	10:54	08:30	05:24	03:12	03:54	18:48	21:00	18:12	15:24	
Minimum	1.69	1.76	2.07	2.23	2.48	2.40	2.50	2.73	2.90	2.97	2.39	1.69	
Min Day	21	12	10	9	6	6	4	23	20	15	17	16	
Min Time	22:00	01:54	12:30	13:06	11:00	12:42	11:36	02:54	01:42	22:48	01:42	01:12	

Dec 20 2018 15:02 GMT

MAXIMUM, MINIMUM WATER LEVEL DATA
National Ocean Service (NOAA)

Station: 8449130
Name: Nantucket Island, MA
Type: Mixed
Note: [] Inferred Water Level Value

T.M.: 0 W
Units: Feet
Datum: StnDatum
Quality: Verified

2009	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
Mean	4.89	4.93	4.82	4.87	4.82	5.31	5.23	5.06	5.14	5.37	5.21	5.15	
Maximum	8.17	7.59	7.62	7.37	7.52	8.64	7.89	7.69	7.72	8.63	7.90	8.16	
Max Day	11	5	30	4	26	23	24	23	13	16	6	20	
Max Time	16:48	12:30	07:00	12:06	05:18	04:12	06:18	06:48	23:30	14:48	18:54	18:06	
Minimum	2.29	2.48	2.13	2.24	2.46	2.81	2.68	2.80	2.82	3.10	2.73	2.15	
Min Day	10	8	12	28	27	25	23	18	20	12	9	12	
Min Time	22:06	21:54	11:42	13:06	12:48	12:30	11:18	08:12	23:48	04:48	03:24	06:54	

2010	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
Mean	5.23	5.36	5.40	5.16	5.07	5.20	5.13	5.17	5.28	5.31	5.32	5.39	
Maximum	8.87	8.44	8.46	8.15	7.93	7.74	7.68	7.68	7.97	7.95	8.46	8.83	
Max Day	2	11	4	28	27	15	12	11	4	9	10	27	
Max Time	17:42	14:36	07:18	04:00	03:48	06:24	04:24	05:00	00:18	17:48	19:30	09:18	
Minimum	1.89	2.23	2.99	2.82	2.64	2.66	2.90	2.91	2.89	2.71	2.61	2.73	
Min Day	29	2	30	3	14	16	13	9	7	8	6	31	
Min Time	22:18	00:42	10:36	14:06	10:48	13:36	11:30	09:30	21:12	22:54	22:48	19:42	

2011	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
Mean	5.07	4.98	4.86	4.91	5.22	5.34	5.28	5.28	5.17	5.39	5.01	4.92	
Maximum	8.24	7.63	8.04	7.56	7.85	8.20	7.88	7.85	7.87	8.85	8.23	8.00	
Max Day	27	21	24	18	17	15	15	11	30	30	24	23	
Max Time	10:30	06:54	08:30	04:12	03:54	03:48	04:18	02:18	18:48	07:12	14:54	14:54	
Minimum	1.95	2.66	2.00	2.26	2.66	3.09	3.11	2.89	2.85	2.82	2.45	2.38	
Min Day	25	16	21	19	18	5	11	31	1	28	26	30	
Min Time	02:36	20:54	11:42	11:30	11:24	13:12	07:06	11:48	00:12	23:54	23:36	02:24	

2012	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
Mean	4.85	4.85	4.86	5.11	4.92	5.32	5.21	5.18	5.09	5.34	5.28	5.25	
Maximum	8.08	7.86	7.23	7.72	7.59	8.74	7.87	7.77	7.44	8.97	8.58	8.02	
Max Day	12	12	29	11	8	5	4	1	19	29	7	18	
Max Time	18:48	07:30	09:18	08:12	06:00	04:36	04:30	03:18	18:54	16:30	23:06	20:48	
Minimum	2.42	2.36	2.14	2.88	2.36	3.05	2.91	3.03	2.88	2.69	2.48	2.22	
Min Day	15	14	11	28	8	7	4	31	20	14	12	12	
Min Time	02:36	02:54	12:48	15:48	12:24	12:54	10:48	10:12	01:06	21:18	21:12	21:54	

Dec 20 2018 15:02 GMT

MAXIMUM, MINIMUM WATER LEVEL DATA
National Ocean Service (NOAA)

Station: 8449130
Name: Nantucket Island, MA
Type: Mixed
Note: [] Inferred Water Level Value

T.M.: 0 W
Units: Feet
Datum: StnDatum
Quality: Verified

2013	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
Mean	4.83	5.03	5.41	4.87	4.90	5.13	5.22	5.24	5.24	5.26	4.99	4.90	
Maximum	7.82	9.80	9.17	7.90	7.96	7.87	8.15	7.66	7.73	7.59	7.79	8.05	
Max Day	12	9	8	1	26	26	24	21	13	12	3	3	
Max Time	17:06	14:54	13:42	08:24	05:00	06:36	05:30	04:18	23:00	22:48	16:06	16:36	
Minimum	2.17	1.91	2.69	2.24	2.22	2.43	3.02	2.85	2.94	3.02	2.64	2.13	
Min Day	10	18	31	27	28	24	22	22	18	9	6	5	
Min Time	21:30	17:18	13:42	11:42	13:24	11:12	10:00	11:12	21:30	01:12	00:00	00:00	

2014	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual

Mean	4.89	4.73	4.88	4.95	5.08	5.14	5.10	5.18	5.15	5.44	5.18	5.11
Maximum	9.57	7.71	9.08	7.60	7.46	7.81	7.57	7.63	7.49	7.99	8.56	7.82
Max Day	3	16	26	1	28	14	14	11	11	3	1	10
Max Time	17:42	05:36	13:30	05:30	04:12	05:06	05:48	04:30	18:24	23:48	23:54	19:18
Minimum	1.89	2.13	2.08	2.50	2.48	2.81	2.56	2.79	2.90	2.83	2.47	2.40
Min Day	30	2	28	20	16	16	12	12	8	11	22	26
Min Time	22:30	00:00	07:54	14:36	11:48	13:18	10:12	11:30	21:36	00:12	22:30	01:42

2015	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
Mean	4.87		4.59	4.80	4.67	4.99	5.24	5.19	5.19	5.29	5.02	5.04	
Maximum	10.21		7.53	7.55	7.29	7.30	7.62	7.60	7.70	7.86	7.81	7.79	
Max Day	27		22	21	20	17	15	10	30	2	11	15	
Max Time	11:06		06:06	06:24	06:12	04:54	03:54	00:54	18:24	20:12	16:30	19:30	
Minimum	2.21		1.51	2.22	2.44	2.70	2.84	2.87	2.37	2.39	1.81	2.41	
Min Day	5		23	17	18	7	6	30	28	27	26	20	
Min Time	23:30		13:00	09:12	10:48	14:12	13:54	10:42	22:36	22:24	23:12	05:18	

2016	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
Mean	5.21	4.95	4.95	5.09	5.06	5.20	5.17	5.09	5.25	5.37	5.25	5.07	
Maximum	8.57	9.08	7.80	8.35	8.28	8.07	7.61	7.36	7.66	8.04	8.10	8.24	
Max Day	24	8	5	3	6	6	3	3	5	18	16	15	
Max Time	16:36	16:24	13:18	13:12	03:42	05:06	03:06	04:42	19:42	18:06	17:48	17:48	
Minimum	2.51	2.25	2.29	2.12	2.42	2.74	2.56	2.85	2.84	2.88	2.40	2.10	
Min Day	19	15	12	11	10	5	4	1	21	20	13	19	
Min Time	19:12	16:24	13:00	13:54	13:36	10:42	10:24	09:12	01:42	01:30	21:18	03:00	

Dec 20 2018 15:02 GMT

MAXIMUM, MINIMUM WATER LEVEL DATA
National Ocean Service (NOAA)

Station: 8449130
Name: Nantucket Island, MA
Type: Mixed
Note: [] Inferred Water Level Value

T.M.: 0 W
Units: Feet
Datum: StnDatum
Quality: Verified

2017	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
Mean	5.04	5.11	4.81	5.11	5.33	5.27	5.30	5.27	5.45	5.22	5.28	4.95	
Maximum	7.78	8.02	7.83	7.87	8.43	8.21	8.03	7.84	8.03	7.55	8.12	7.94	
Max Day	24	9	14	2	26	24	23	20	21	30	8	6	
Max Time	14:24	15:42	20:06	08:42	04:36	04:12	04:06	02:54	17:48	13:36	19:48	18:48	
Minimum	2.17	2.19	2.08	2.21	2.79	2.72	2.91	2.95	3.18	3.02	2.84	2.22	
Min Day	13	10	4	29	1	25	22	21	11	11	7	28	
Min Time	23:48	22:42	15:12	13:00	14:54	11:36	09:24	10:00	01:48	02:36	00:30	18:12	

2018	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
Mean	4.78	4.68	5.68	4.99	5.02	5.30	5.09	5.29	5.33	5.36	5.21		
Maximum	10.30	7.60	9.73	7.58	7.61	8.22	7.89	7.98	7.87	8.37	8.71		
Max Day	4	5	3	18	18	15	12	10	10	12	25		
Max Time	18:48	08:42	17:42	06:12	06:36	05:30	03:24	03:06	04:48	19:06	17:54		
Minimum	1.34	2.13	2.77	2.45	2.53	2.56	2.61	2.91	2.97	2.93	2.04		
Min Day	6	3	31	22	19	13	14	12	7	9	4		
Min Time	02:00	12:36	10:36	15:54	13:54	10:12	11:42	11:12	08:00	22:48	07:36		

*The monthly max/min report information is based on high/low tides only.

Figure 16: October 1991 "Perfect Storm"; Peak water level = 6.11 feet MSL = 5.8 feet NAVD88; Maximum sustained wind speed = +/- 40 kts (46 mph) from the northeast (Source: https://tidesandcurrents.noaa.gov/waterlevels.html?id=8449130&units=standard&bdate=20150123&edate=20150131&timezone=GMT&datum=MSL&interval=h&action=

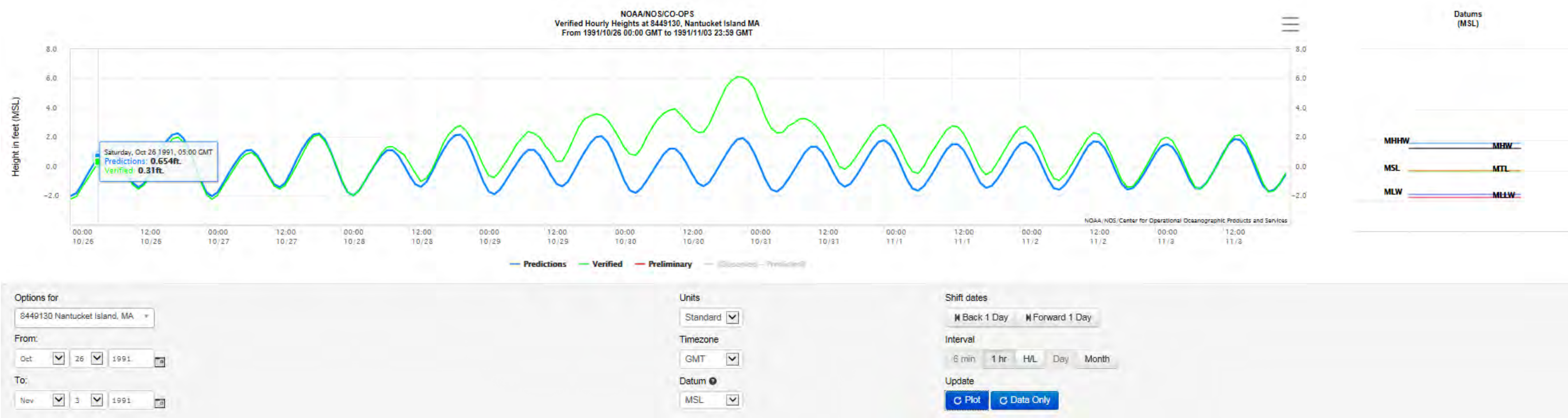


Figure 17: Hurricane Bob, August 19, 1991; No elevated water level (<1-foot storm surge)
(Source: https://tidesandcurrents.noaa.gov/waterlevels.html?id=8449130&units=standard&bdate=20150123&edate=20150131&timezone=GMT&datum=MSL&interval=h&action=

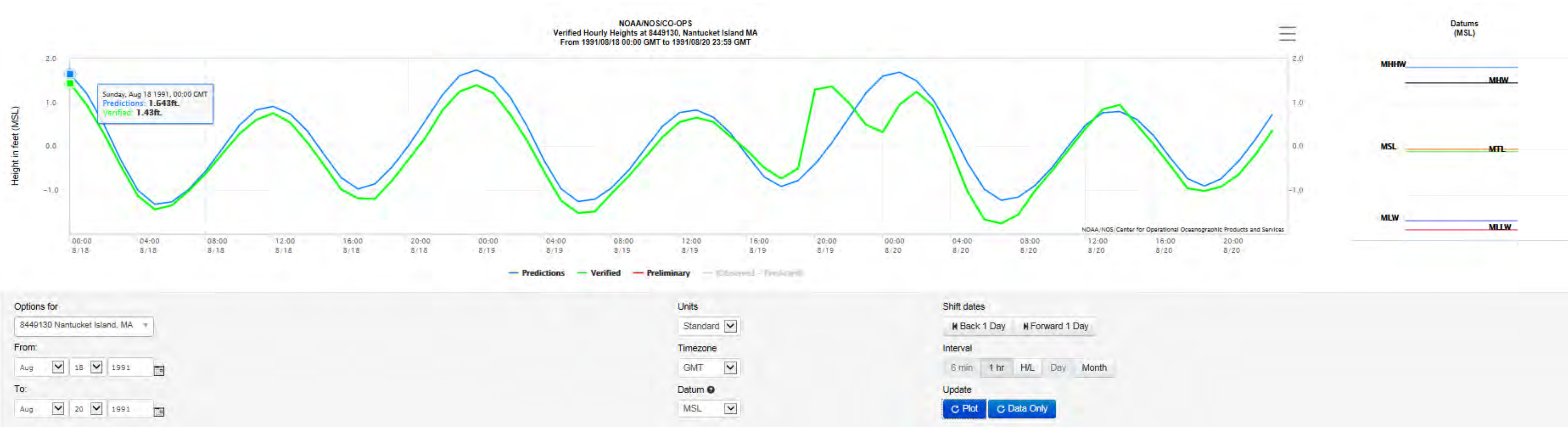


Figure 18: January 27, 2015 Nor'easter
(Source: https://tidesandcurrents.noaa.gov/waterlevels.html?id=8449130&units=standard&bdate=20150123&edate=20150131&timezone=GMT&datum=MSL&interval=h&action=

Peak water level = 5.21 feet MSL = 4.9 feet NAVD88; Maximum sustained wind speed = +/- 40 kts (46 mph) from the northeast

Figure 19: January 27, 2015 Nor'easter January 27th Surface Weather Map

(Source: https://tidesandcurrents.noaa.gov/waterlevels.html?id=8449130&units=standard&bdate=20150123&edate=20150131&timezone=GMT&datum=MSL&interval=h&action=

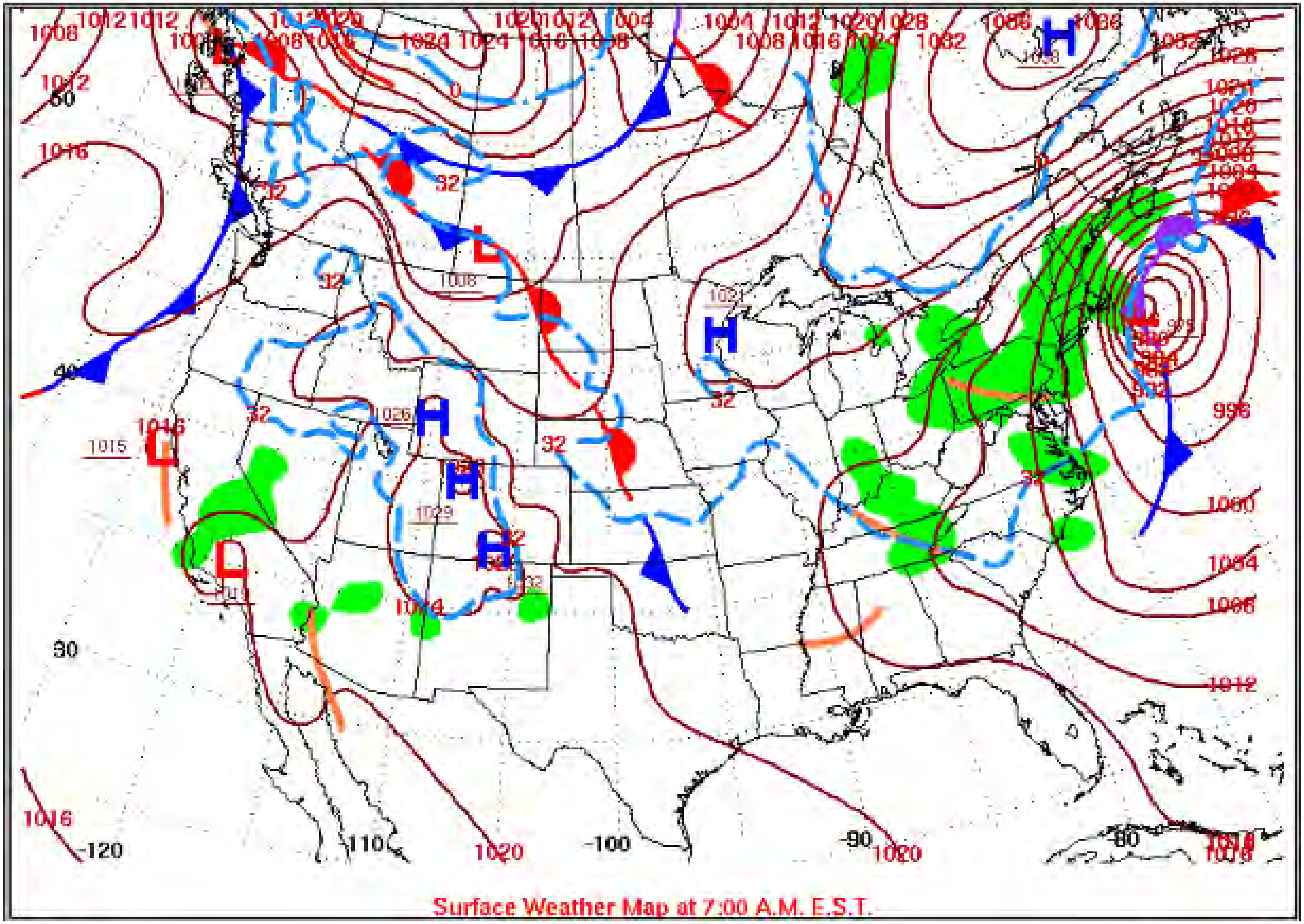
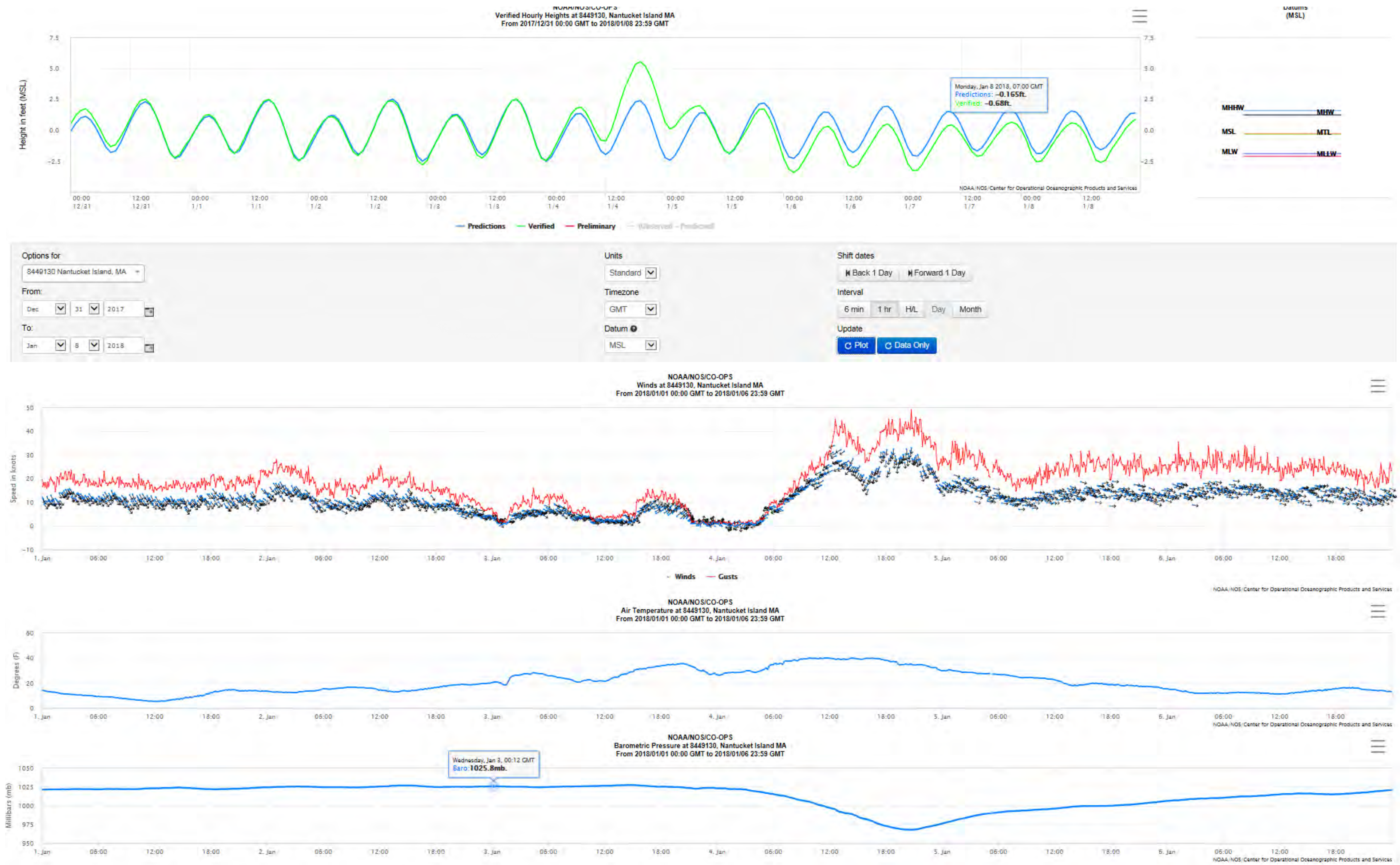


Figure 20: January 4, 2018 Nor'easter

(Source: https://tidesandcurrents.noaa.gov/waterlevels.html?id=8449130&units=standard&bdate=20150123&edate=20150131&timezone=GMT&datum=MSL&interval=h&action=



Peak water level = 5.6 feet MSL = 5.3 feet NAVD88; Maximum sustained wind speed = +/- 30 kts (35 mph) from the northeast to north

Figure 21: January 4, 2018 Nor'easter January 4th Surface Weather Map
(Source: https://tidesandcurrents.noaa.gov/waterlevels.html?id=8449130&units=standard&bdate=20150123&edate=20150131&timezone=GMT&datum=MSL&interval=h&action=

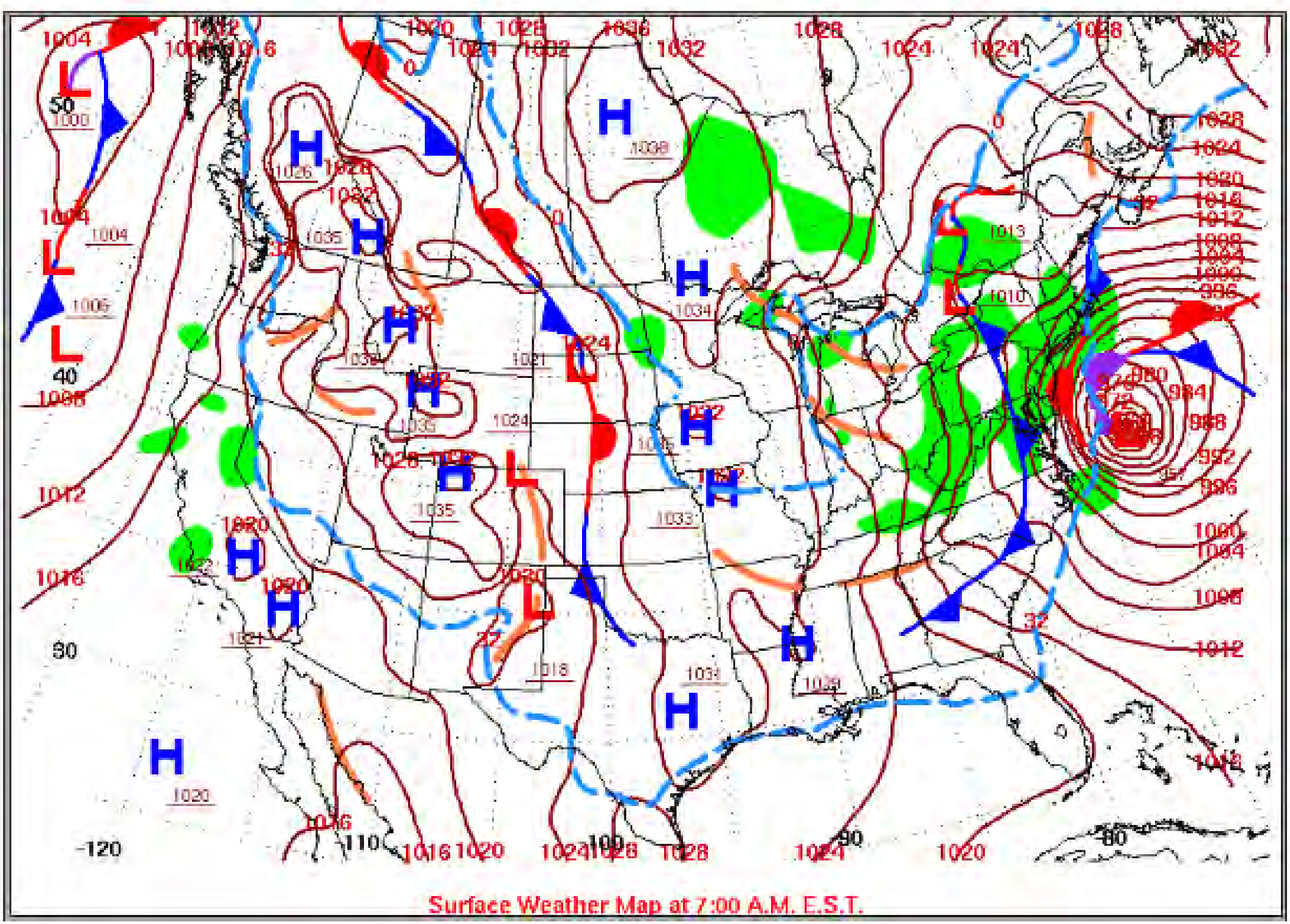
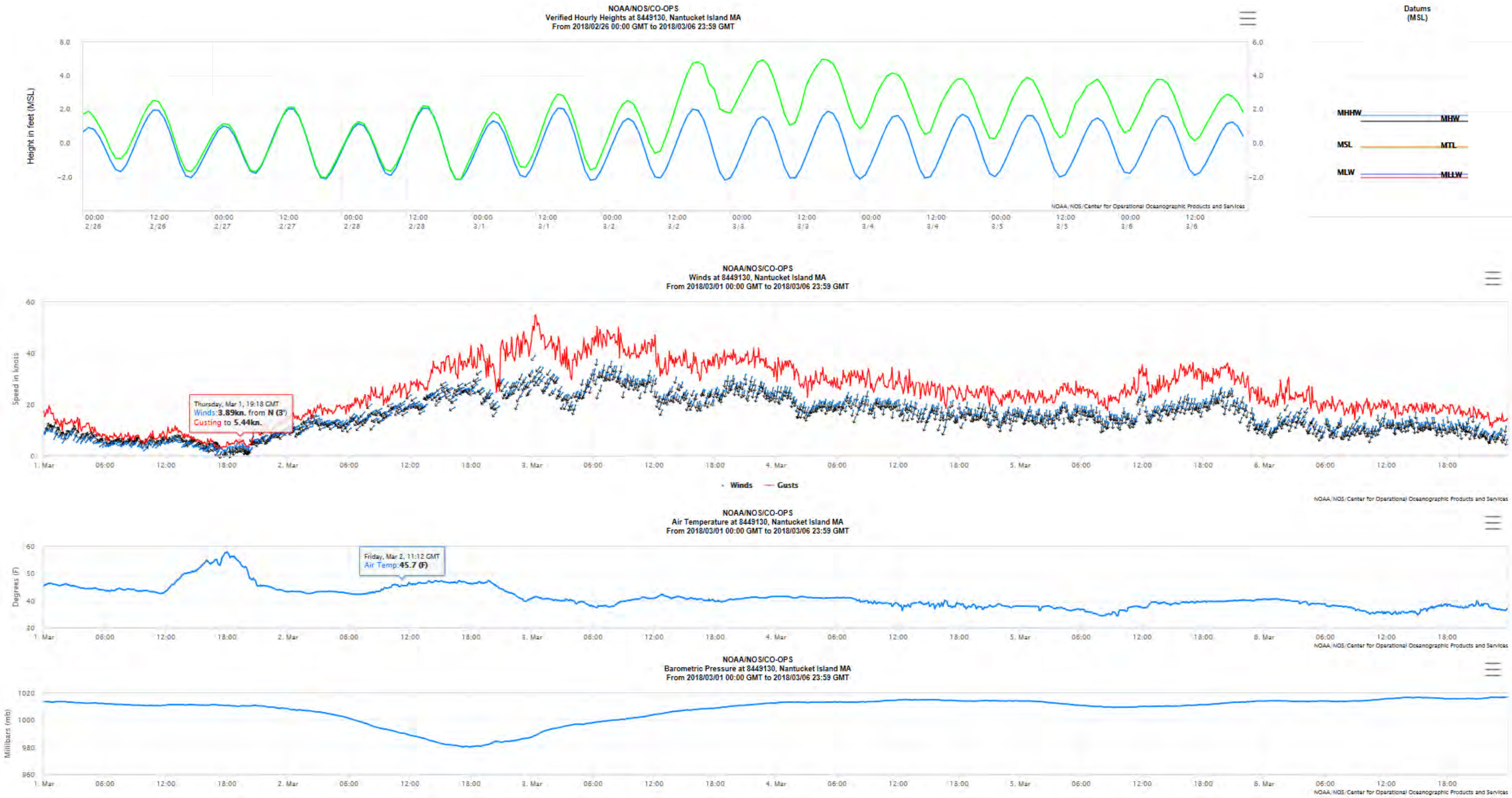


Figure 22: March 3-4, 2018 Nor'easter

(Source: https://tidesandcurrents.noaa.gov/waterlevels.html?id=8449130&units=standard&bdate=20150123&edate=20150131&timezone=GMT&datum=MSL&interval=h&action=



Peak water level = 5 feet MSL = 4.8 feet NAVD88; Maximum sustained wind speed = +/- 35 kts (40 mph) from the northeast to north

Figure 23: March 3-4, 2018 Nor'easter March 3rd Surface Weather Map

(Source: https://tidesandcurrents.noaa.gov/waterlevels.html?id=8449130&units=standard&bdate=20150123&edate=20150131&timezone=GMT&datum=MSL&interval=h&action=

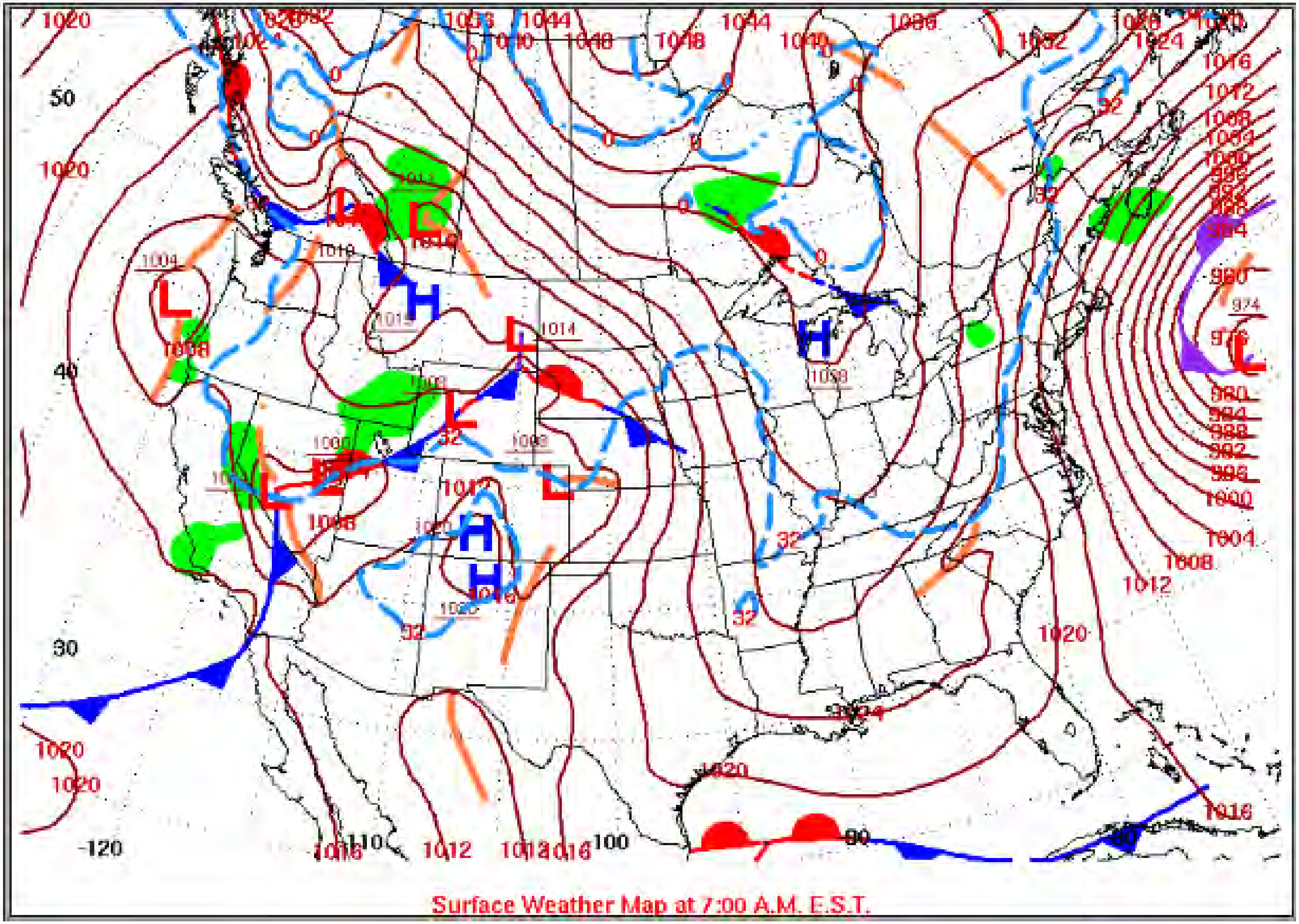
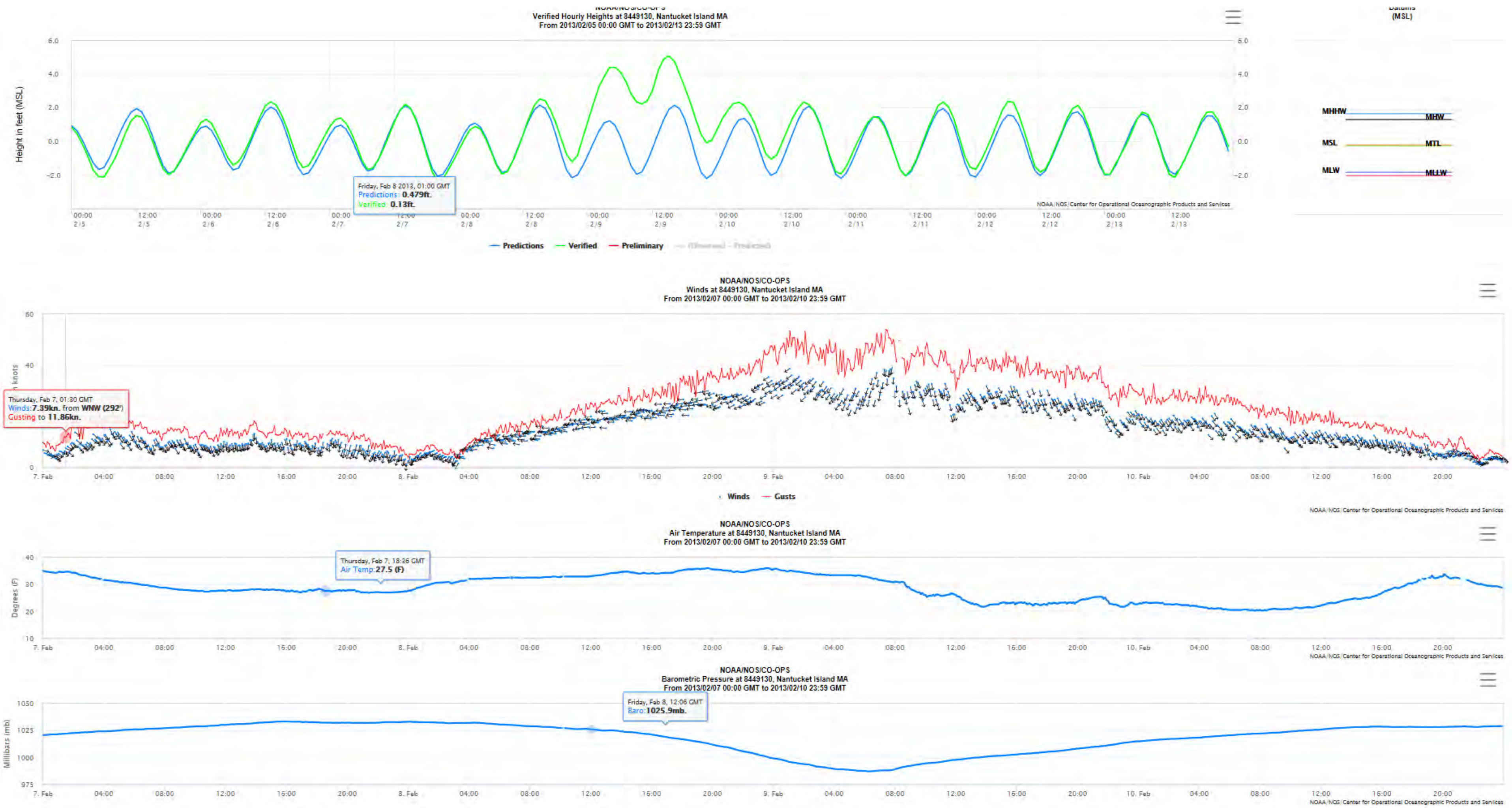


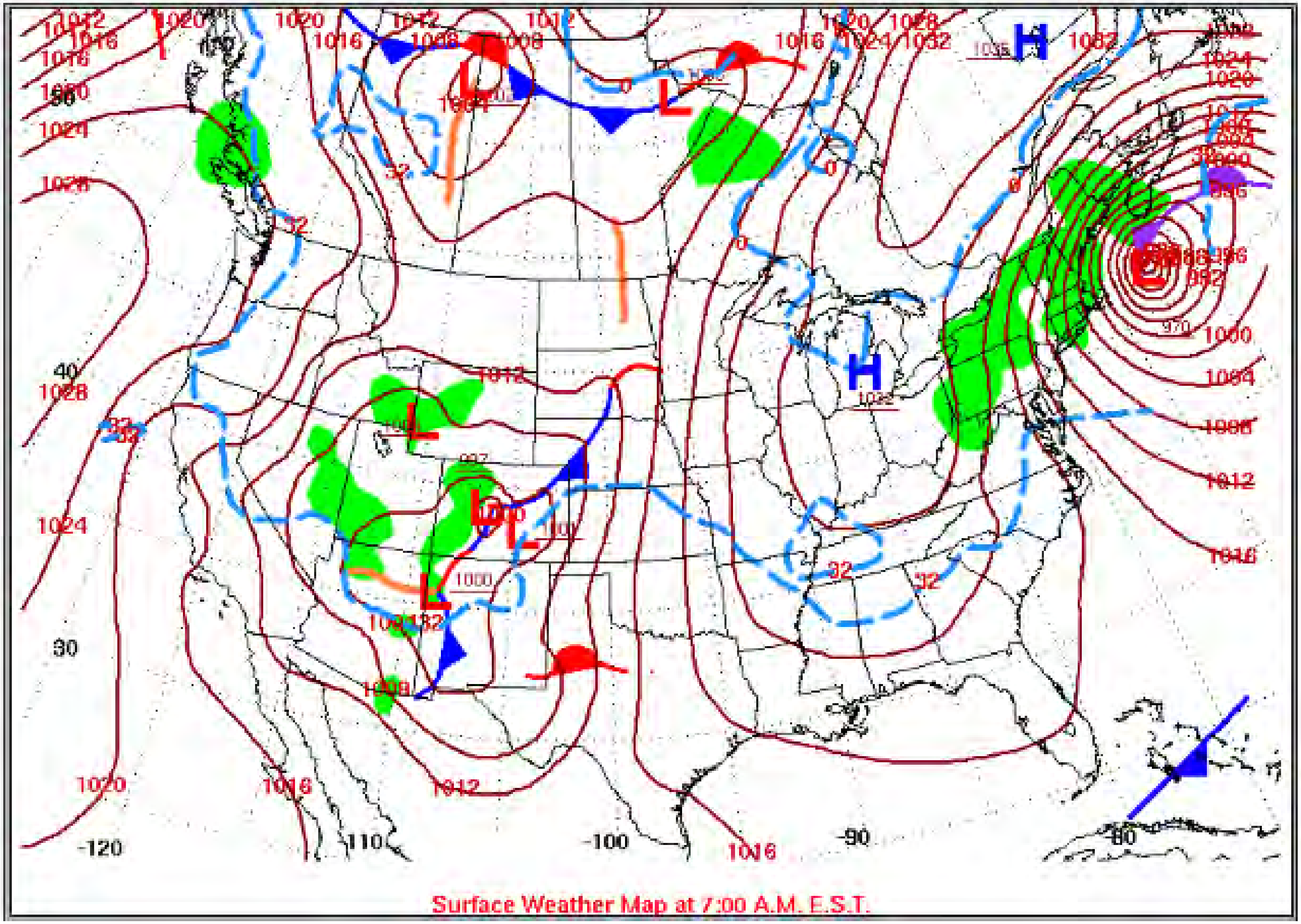
Figure 24: February 9, 2013 Nor'easter

(Source: https://tidesandcurrents.noaa.gov/waterlevels.html?id=8449130&units=standard&bdate=20150123&edate=20150131&timezone=GMT&datum=MSL&interval=h&action=



Peak water level = 5.1 feet MSL = 4.83 feet NAVD88; Maximum sustained wind speed = +/- 40 kts (46 mph) from the northeast to north

Figure 25: February 9, 2013 Nor'easter February 9th Surface Weather Map
(Source: https://tidesandcurrents.noaa.gov/waterlevels.html?id=8449130&units=standard&bdate=20150123&edate=20150131&timezone=GMT&datum=MSL&interval=h&action=



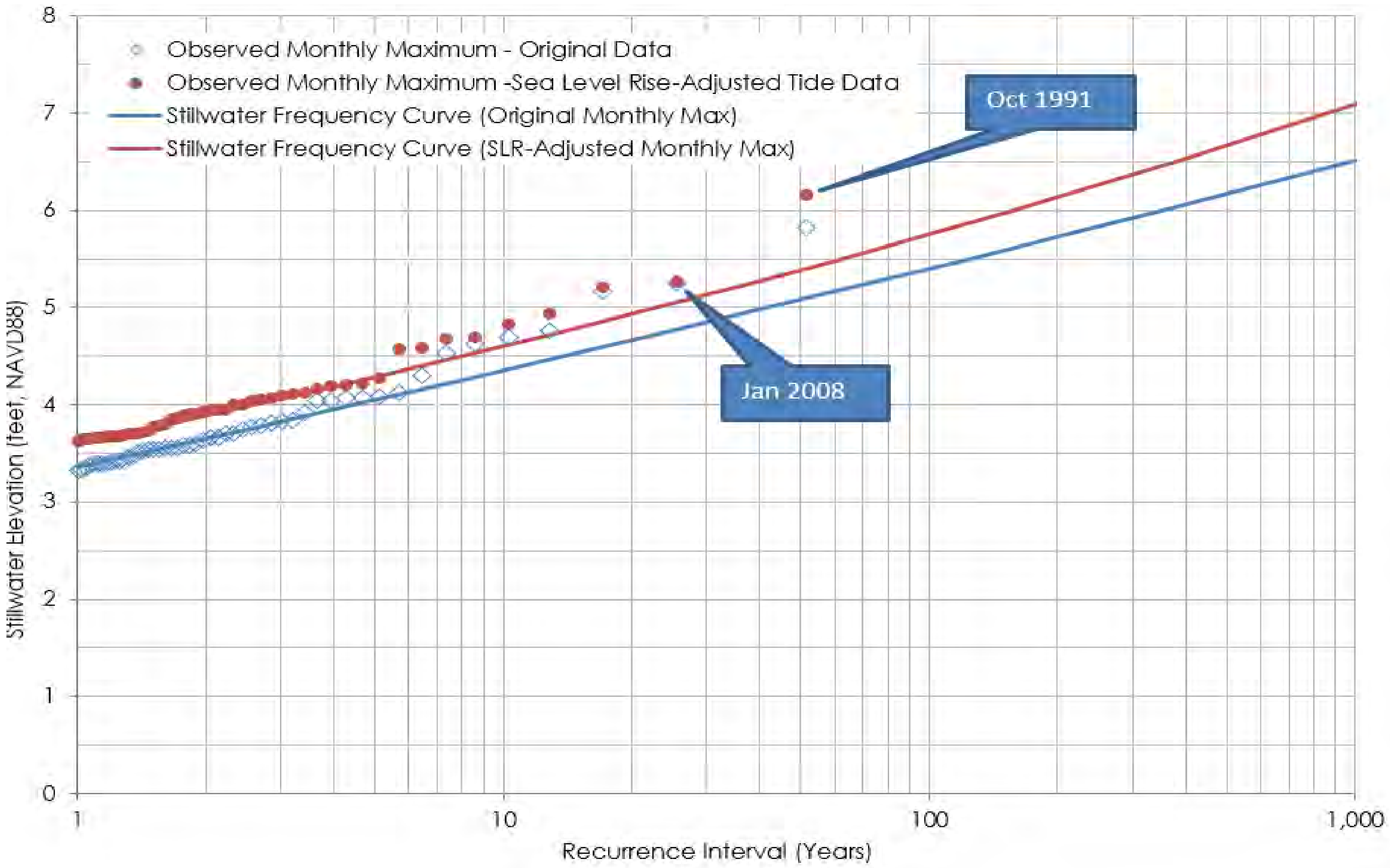


Figure 26: Generalized Extreme Value Stillwater Flood Frequency Relationship (based on Monthly Peak Water Level Data and corrected for observed sea level rise)

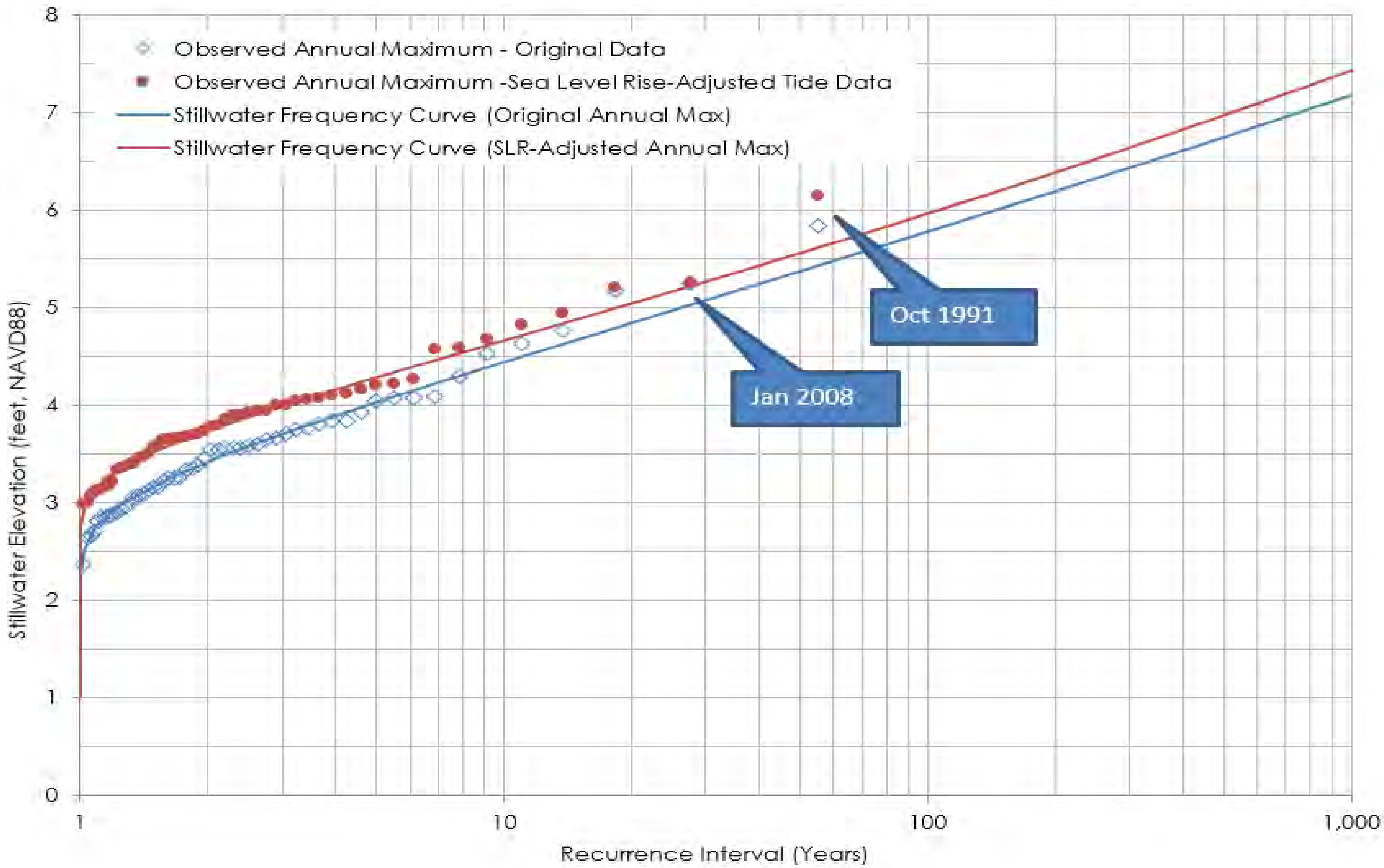
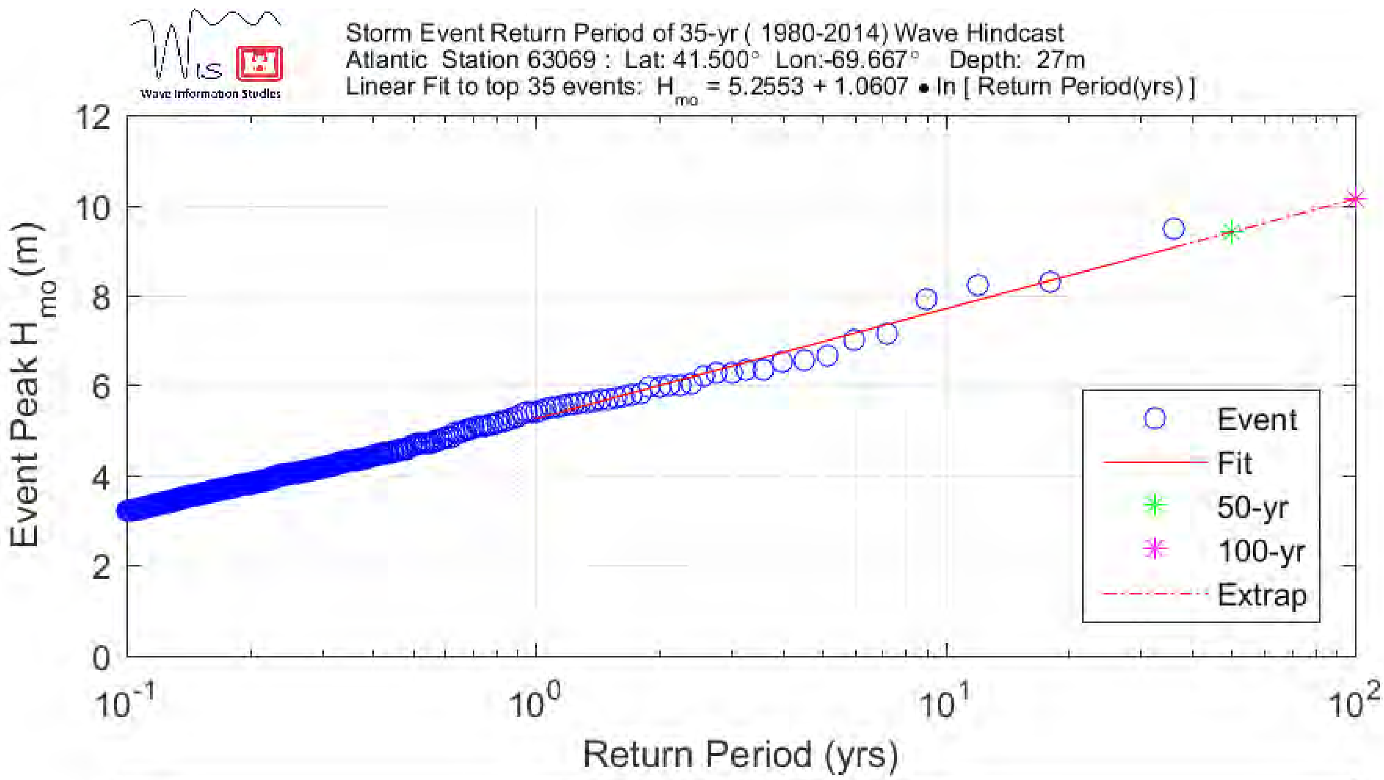
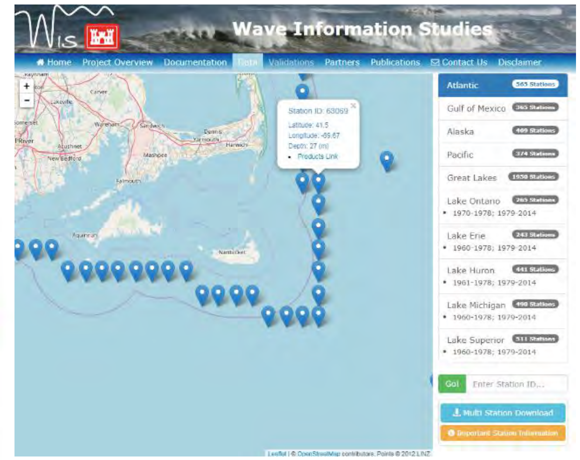


Figure 27: Generalized Extreme Value Stillwater Flood Frequency Relationship (based on Annual Peak Water Level Data and corrected for observed sea level rise)

Figure 28: USACE Wave Information Studies Station 6309 Wave Statistics and Top 10 Wave Events (1980 – 2014)





Top 10 events based on Peak H_{mo}

Event	Date/Time(UTC)	H_{mo}	T_p	θ_{mean}	Event	Date/Time(UTC)	H_{mo}	T_p	θ_{mean}
1	1991/10/31 01:00	9.49	19.33	60.0	6	2007/11/04 00:00	7.02	16.48	86.0
2	1992/12/12 23:00	8.28	15.09	61.0	7	2013/03/07 13:00	6.64	12.25	53.0
3	2012/10/29 21:00	8.23	14.06	86.0	8	1980/02/08 03:00	6.56	11.65	41.0
4	1980/01/16 13:00	7.90	13.34	52.0	9	1984/03/30 01:00	6.50	12.07	60.0
5	2004/12/27 07:00	7.13	14.27	52.0	10	2010/03/14 11:00	6.36	12.47	86.0

An event is defined as any period when H_{mo} > 3.00m θ_{mean} is direction that waves are arriving from

ERDC US Army Engineer Research & Development Center   ST63069_v03

ATTACHMENT 4
Wind Analysis

WIND ANALYSIS

GZA performed an analysis of wind intensity and direction for the purpose of developing 3-second gust and 1-minute, sustained 10-meter winds for use in Town Pier load calculations. Wind intensity values were developed for multiple recurrence intervals (annual exceedance probabilities [AEP]). Wind intensity values were also developed at the bounds of GZA's numerical wave model domain to develop wave model wind intensity and direction input. Wind data sources included:

1. ASCE/SEI 7-10 Minimum Design Loads for Buildings and Other Structures. ASCE/SEI presents 3-second gust wind speeds for multiple Risk Factor structures and multiple recurrence intervals. The ASCE/SEI 7-10 wind speeds applicable to Nantucket reflect hurricane-dominated wind events (i.e., hurricane prone region). GZA converted the 3-second gusts to 1-minute and 10-minute sustained wind speeds using wind speed conversion factors for tropical cyclones presented in "Guidelines for Converting between Various Wind Averaging Periods in Tropical Cyclone Conditions", World Meteorological Organization, 2008.

2. GZA Metocean Data and Modeling Program (GZA MDMP). The converted ASCE/SEI 7-10 wind speeds were compared (for consistency) to GZA's metocean analysis data which includes regional statistical distributions of tropical cyclone meteorological parameters along the US East Coast and Gulf. GZA's data incudes extreme values analyses using the Peak Over Threshold (POT) method to develop statistical distributions of the NOAA HURDAT2 6-hour, 1-minute maximum wind velocities for a 1.5º by 1.5º regions representative of Nantucket conditions. GZA's values generally represent "At-Sea" values.

3. Nantucket Airport. GZA performed a General Extreme Value (GEV) analysis of hourly, 1 and 2-minute, 10-meter sustained wind speeds. The period of record for Nantucket Airport wind data is 71years (1948 to current). GZA's GEV analysis evaluated annual peak wind speeds (recorded in miles per hour). GZA performed GEV analysis for "all-direction" winds and for directional winds by compass quadrant. GZA reviewed the data record relative to representative peak wind events to identify the contributing storm type (i.e., nor-easter, tropical cyclone, thunderstorm, tornado). The contributing storm type was determined based on event date and available historical storm information. Unless available information indicates otherwise, very short duration high wind events were assumed to be due to local thunderstorms.

4. NOAA National Data Buoy Center Station NTKM3 - 8449130 - Nantucket Island, MA. GZA reviewed historical wind data for this land station, available for the period of November 2008 through December 2012. The data includes: a) 2-minute average wind speed by month; b) 5-second gust speed by month; c) peak gust speed; and d) 2-minute average wind speed by direction, and provides statistical representation of prevailing wind conditions.

5. USACE Wave Information Studies (WIS). GZA reviewed USACE WIS wind direction data for an available year (2014) to assess representative nearby ocean annual wind direction data.

Correlations between peak water levels and peak wind intensity were performed to evaluate the probability of experiencing coincident, combined high water level and high wind load conditions.

Wind Direction and Intensity

ASCE 7-10

The ASCE/SEI 7-10 wind speeds were developed for Nantucket Town Pier using the Applied Technology Council search tool. The ASCE 7-10 specified 3-second gust for the Nantucket Town Pier is 120 miles per hour (mph) for the 100-year recurrence interval (1% AEP). This value is converted to a 1-minute sustained wind speed at 10 meters height of approximately 98 mph and a 10-minute sustained wind speed at 10 meters of approximately 87 mph. The gust duration conversion is associated off-sea to onshore winds at a coastline.

Table 1- ASCE/SEI 7-10 wind speeds (3-second gust and converted 1-minute sustained wind speeds)

Recurrence Interval (yrs)	Wind Speed (3sec, mph)	Wind Speed (1min, mph)	Wind Speed (10min, mph)
10	80	65	58
25	100	81	73
50	109	89	79
100	120	98	87
300	139	113	101
700	140	114	102
1,700	158	128	115

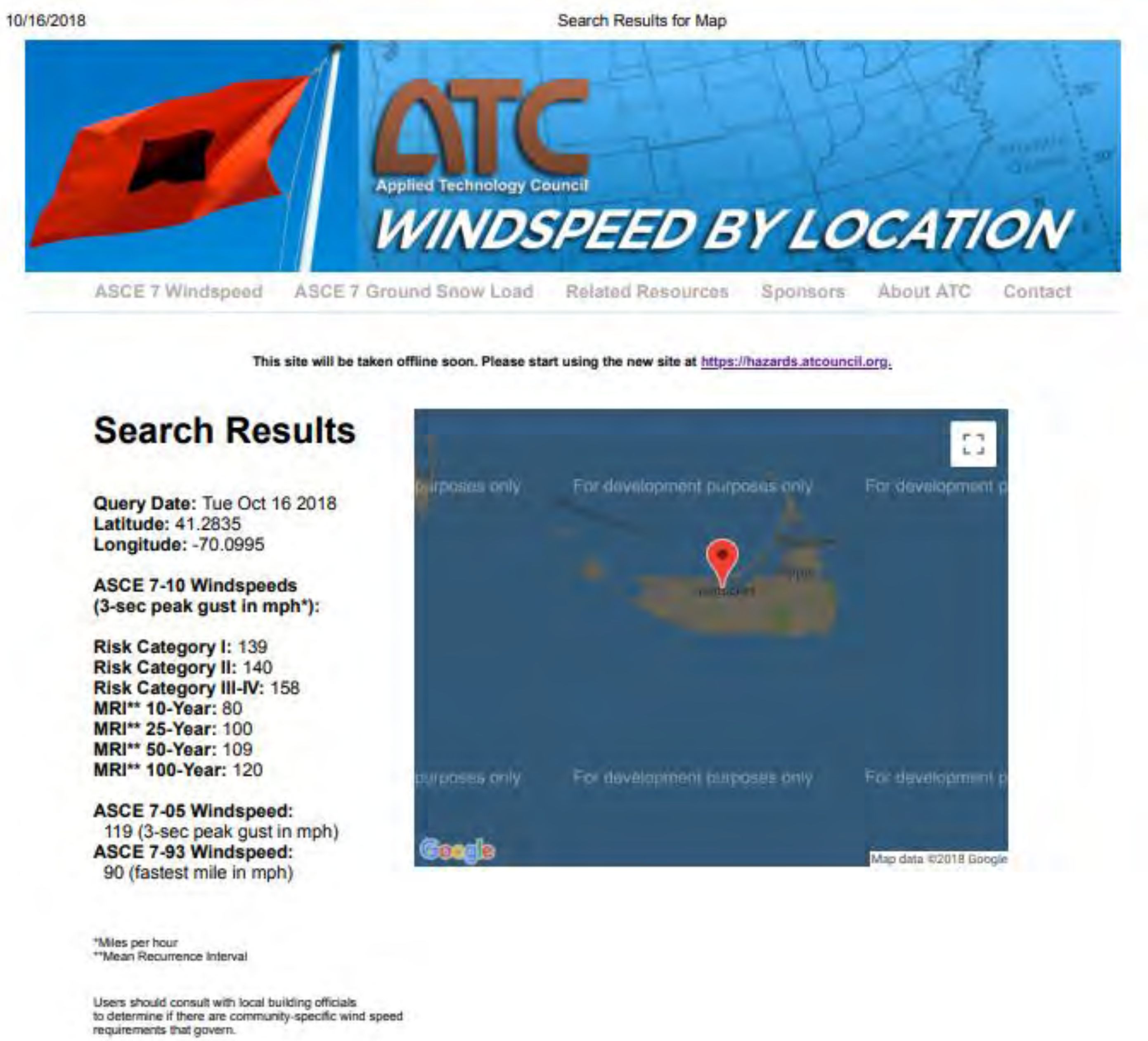


Figure 1: ASCE/SEI 7-10 wind speeds (3-second gust) using AST Search Tool

GZA MDMP

The converted ASCE/SEI 7-10 wind speeds were compared (for consistency) to GZA's metocean analysis data (GZA MDMP) which includes regional statistical distributions of tropical cyclone meteorological parameters along the US East Coast and Gulf. GZA's distribution values generally represent "At-Sea" values. A comparison of the ASCE/SEI 7-10 wind speeds converted for "At-Sea" conditions, 1-minute averaging duration and mph to knots is presented below. The hNE HURDAT2 subregion incorporates Nantucket. The results indicate consistency between HURDAT2 and ASCE 7-10 wind speed estimations.

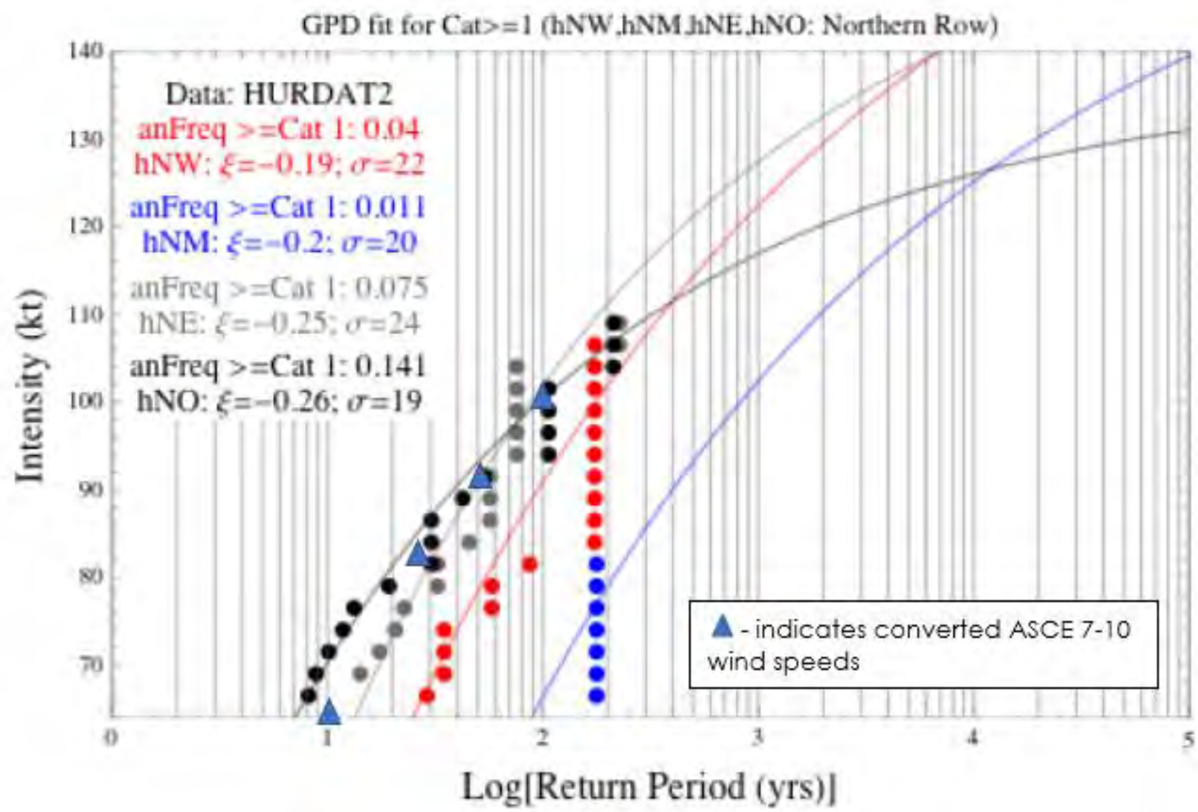


Figure 2 – Comparison of ASCE/SEI 7-10 wind speeds (converted 1-minute) and GZA MDMP HURDAT2 AT-Sea wind speeds in the vicinity of Nantucket

Nantucket Airport – GZA Statistical Analysis and Wind Frequency Curve

GZA also performed an independent wind frequency analysis of area wind speed and directionality. Hourly wind data at the Nantucket Memorial Airport, located near the project site at Longitude: -70.061°, Latitude: 41.253°, was downloaded from the National Climatic Data Center (NCDC) and statistically analyzed. The period of record covers 1948 to present, a total of 71 years. The maximum wind speeds (1 and/or 2 minute sustained wind speed) relative to different directional quadrants and "all direction" are summarized below. Extreme value statistical analysis was performed based on the monthly and annual maximum wind speed values extracted from the dataset. The wind frequency curve was based on the best fit using the Generalized Extreme Value (GEV) distributions. The North quadrant represents northerly winds with 315° to 45° compass (NW to NE) from true north. The East quadrant represents easterly winds with 45° to 135° compass (NE to SE) from true north. The South quadrant represents southerly winds with 135° to 225° compass (SE to SW) from true north. The West quadrant represents westerly winds with 225° to 135° compass (SW to NW) from true north. All-direction 3-second gust data was also analyzed using GEV.

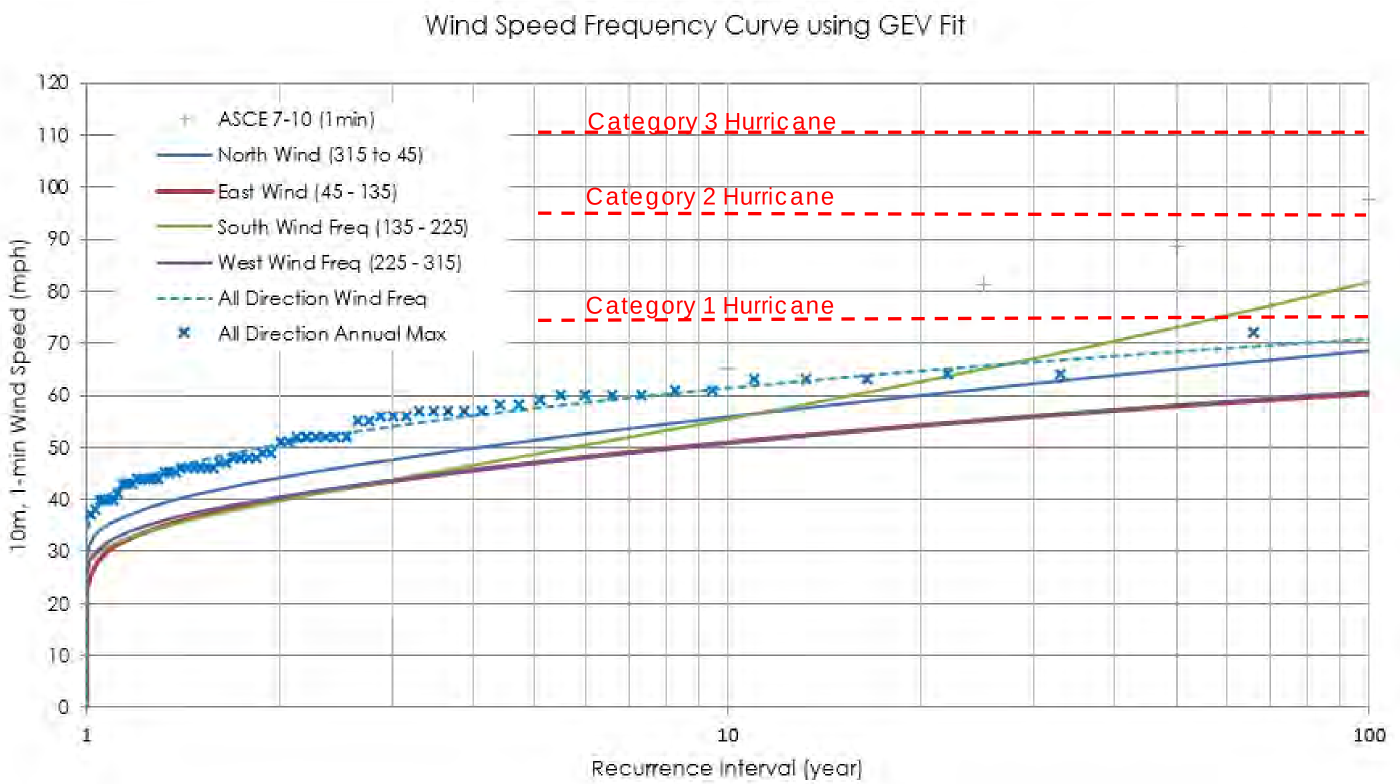


Figure 3 – GZA GEV analysis of Nantucket Airport Wind Speeds (1-minute, 10-meter); ASCE/SEI 7-10 converted wind speeds shown for comparison

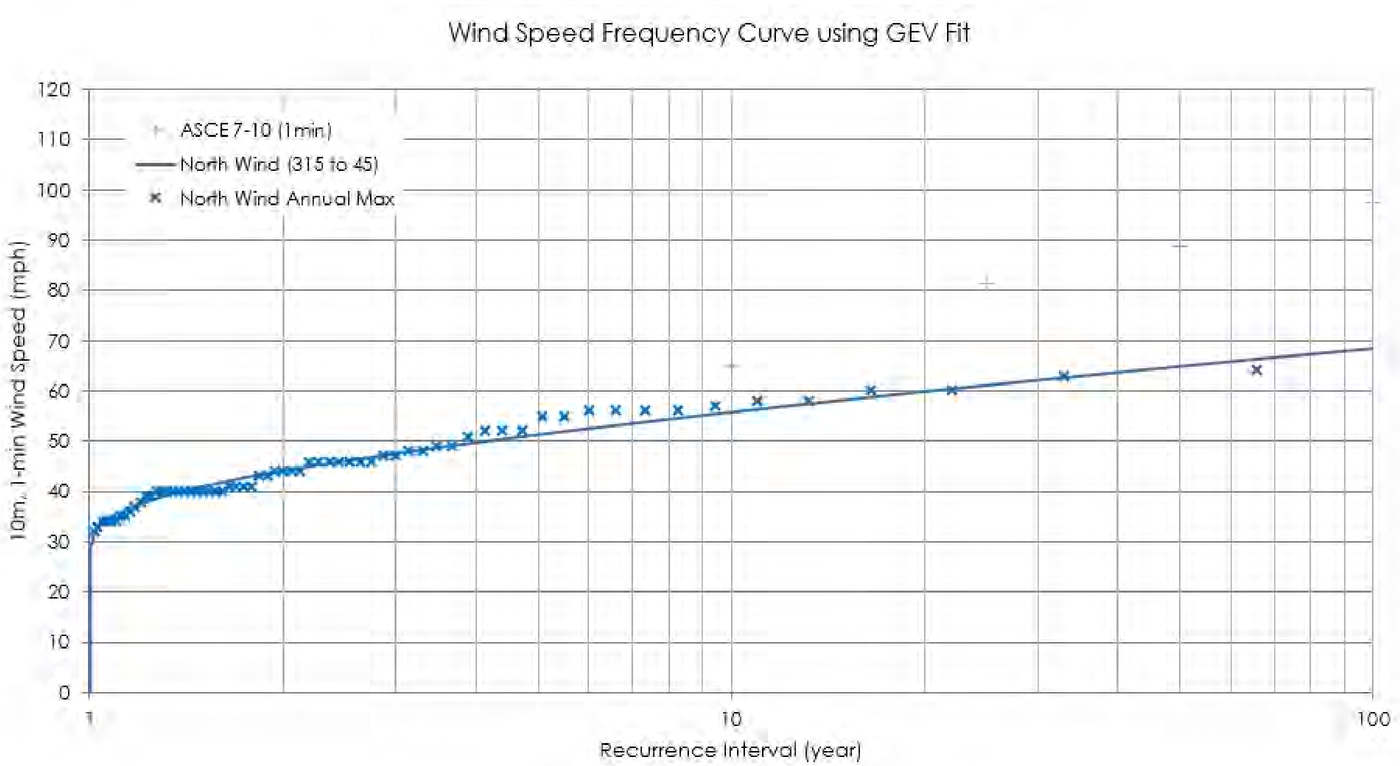


Figure 4 – GZA GEV analysis of Nantucket Airport Wind Speeds (North 1-minute, 10-meter); ASCE/SEI 7-10 converted wind speeds shown for comparison

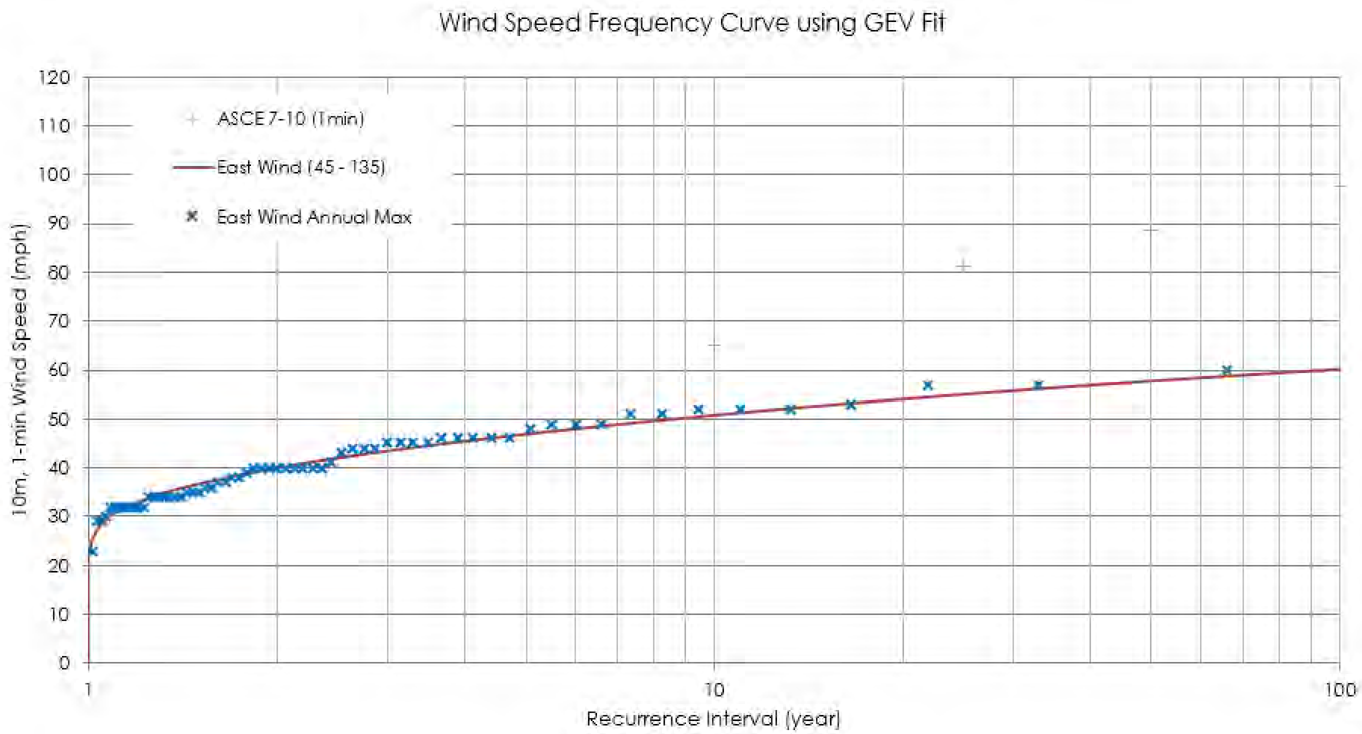


Figure 5 – GZA GEV analysis of Nantucket Airport Wind Speeds (East 1-minute, 10-meter); ASCE/SEI 7-10 converted wind speeds shown for comparison

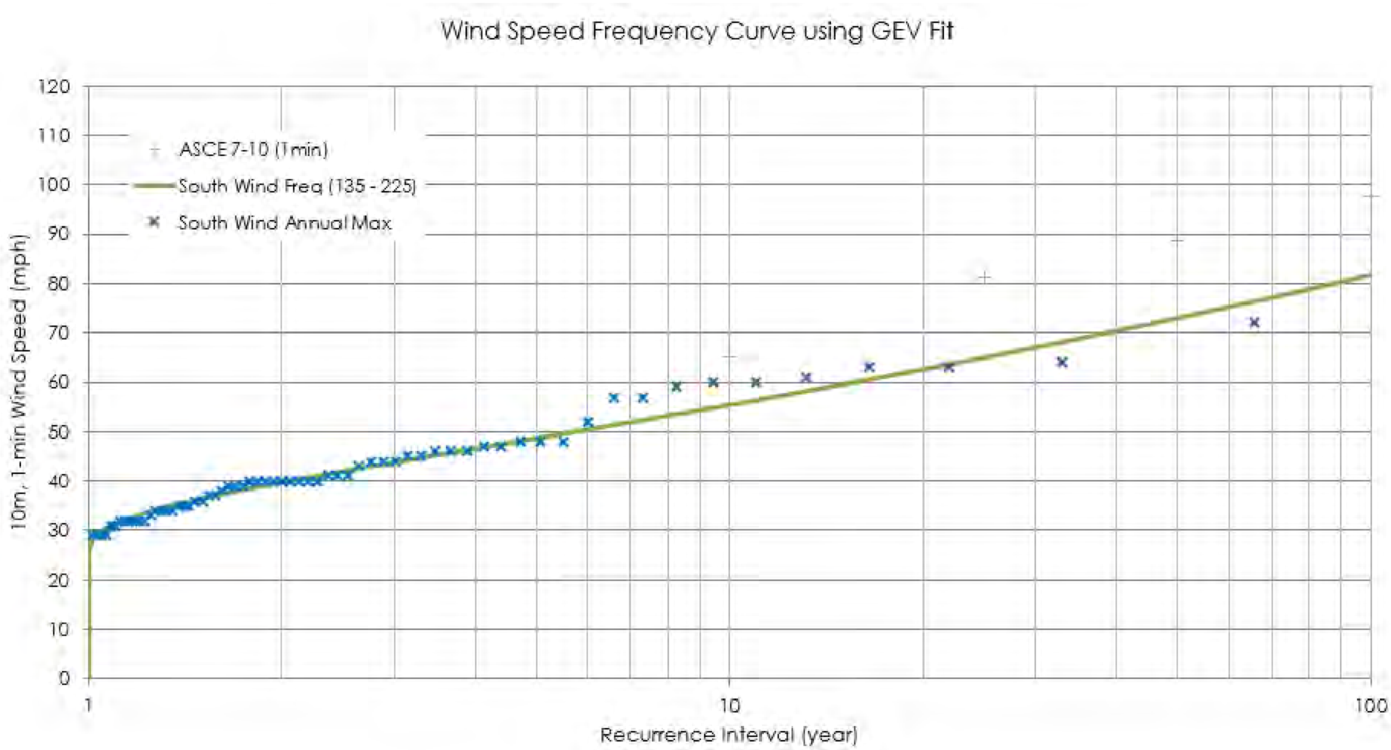


Figure 6 – GZA GEV analysis of Nantucket Airport Wind Speeds (South 1-minute, 10-meter); ASCE/SEI 7-10 converted wind speeds shown for comparison

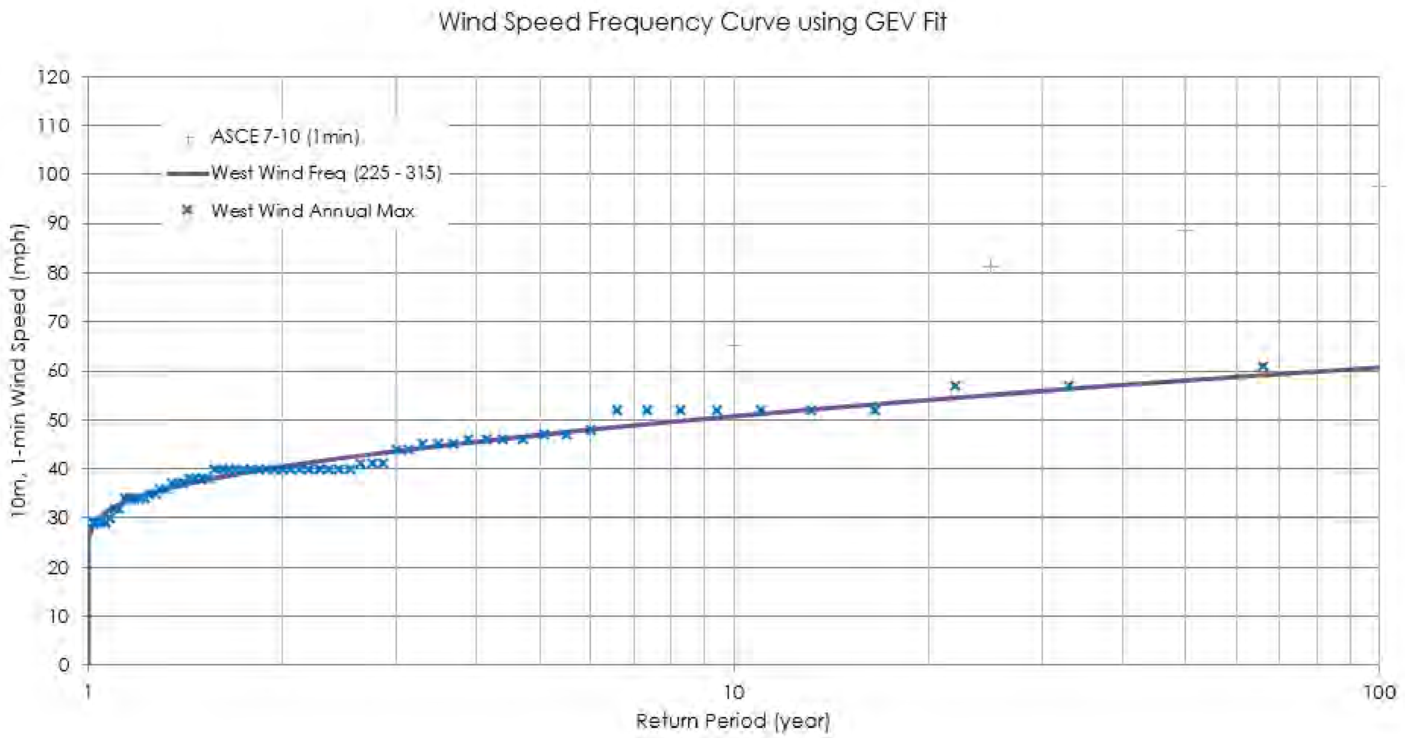


Figure 7 – GZA GEV analysis of Nantucket Airport Wind Speeds (West 1-minute, 10-meter); ASCE/SEI 7-10 converted wind speeds shown for comparison

The annual peak wind events within each quadrant are summarized below.

Table 1 - Nantucket Memorial Airport Hourly Wind (1948 to Present).

Direction	Maximum Wind Speed (mph)[1]	Occurrence Date
North Wind (315 º to 45º)	64	11/13/2014
East Wind (45 º - 135 º)	60	6/20/1974
South Wind Freq (135 º - 225 º)	72	9/2/1984
West Wind Freq (225 º - 315 º)	61	2/17/1982
All Direction Wind	72	9/2/1984

Notes:
1. Wind duration is 1-minute, 10-meter sustained wind speed.

The all-direction annual 3-second gust data was also analyzed for comparison to ASCE 7-10. Similar to the 1, 2-minuted sustained wind data, the observed 3-second gust speeds are significantly lower than ASCE 7-10.

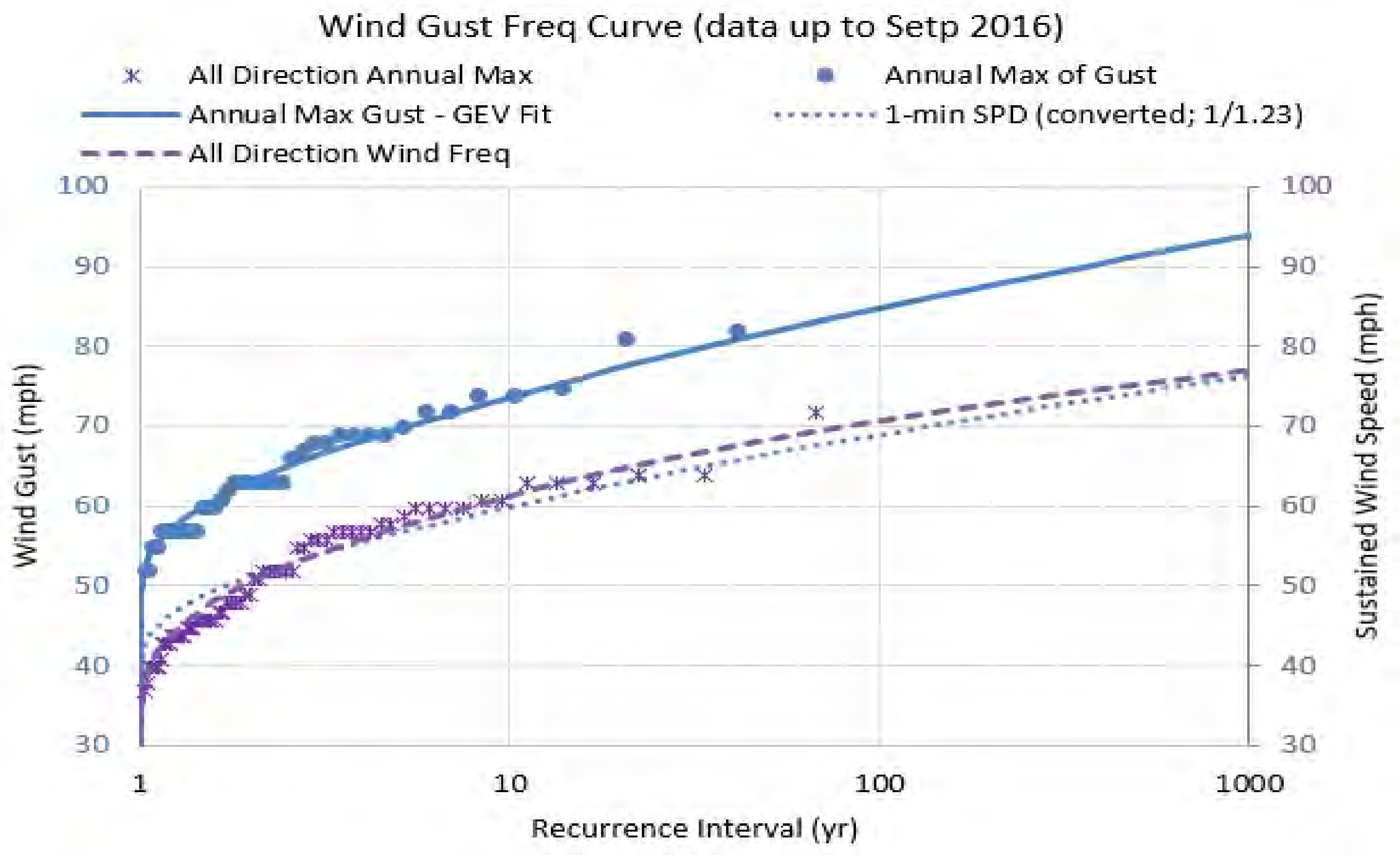
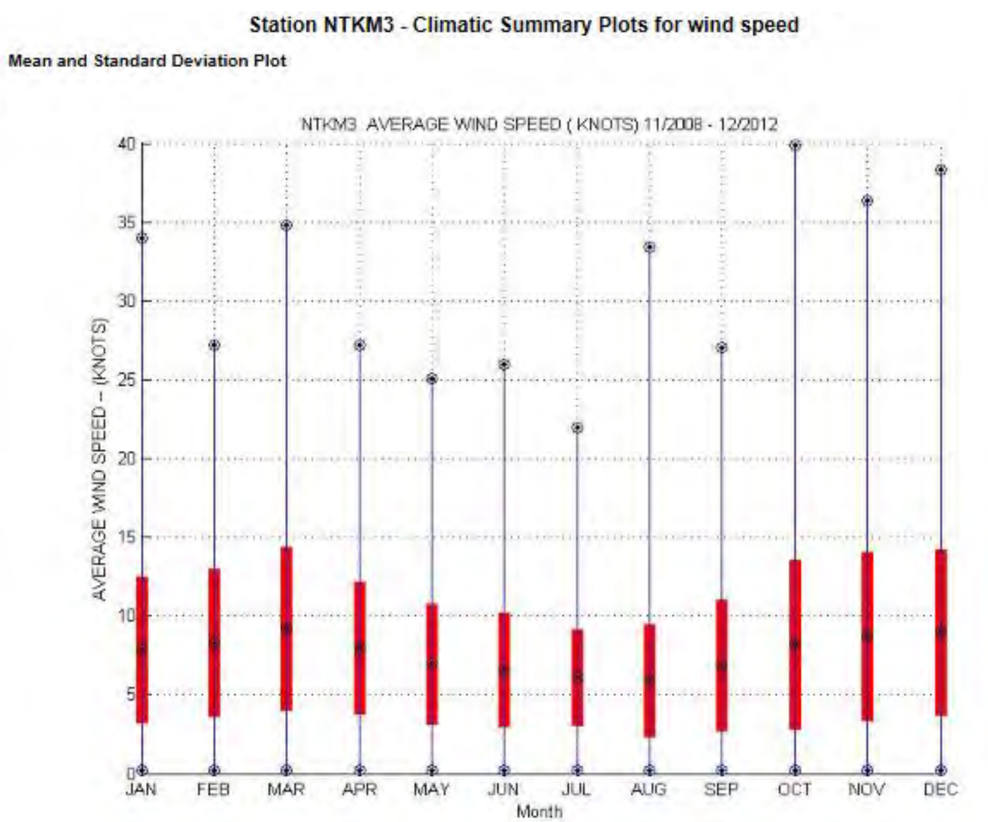


Figure 8 – GZA GEV analysis of Nantucket Airport Wind Speeds (all direction 3-second gust and 1-minute, 10-meter)

NOAA Land Station Data – Prevailing Wind Conditions

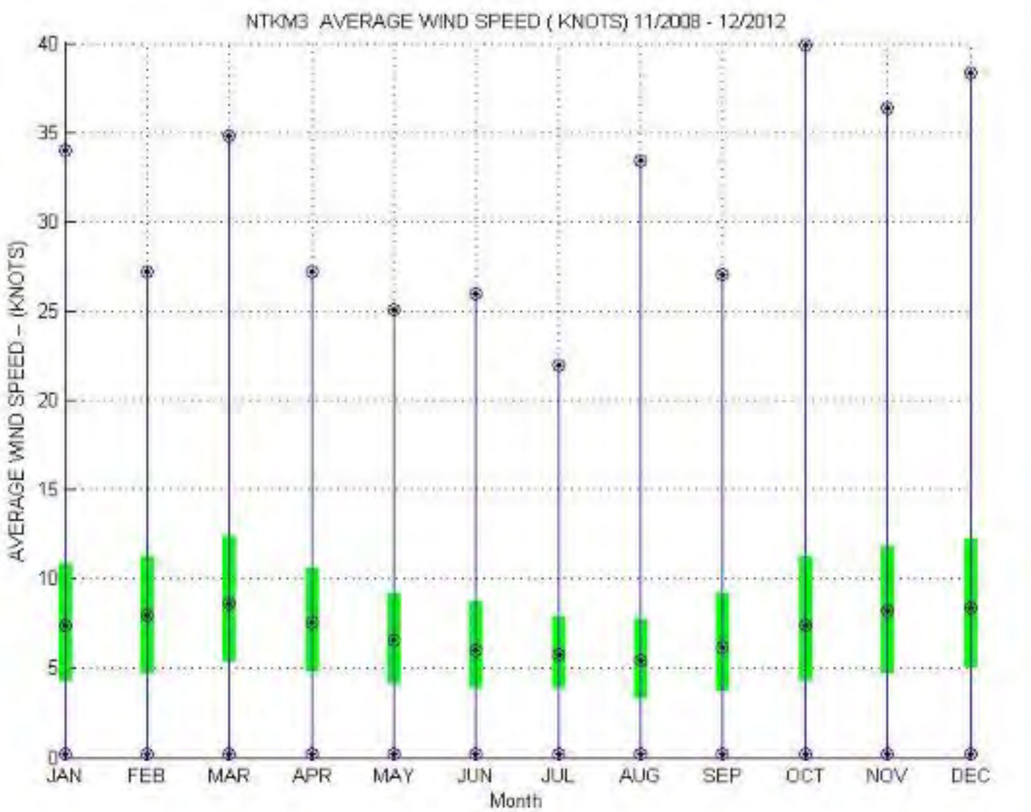
GZA reviewed historical wind data for the NOAA National Data Buoy Center Station NTKM3 - 8449130 - Nantucket Island, MA (a land station), available for the period of November 2008 through December 2012. The data includes: a) 2-minute average wind speed by month; b) 5-second gust speed by month; c) peak gust speed; and d) 2-minute average wind speed by direction.

The 2-minute averaged wind speed annually (by month):



The top blue dot-within-the-circle indicates the maximum value for the month. The top of the red bar indicates the value of one (1) Standard Deviation above the Mean Value. The bottom blue dot-within-the-circle indicates the Minimum Value. The blue dot-within-the circle in the middle of the red bar indicates the Mean or Average value. The bottom of the red bar indicates the value one (1) Standard Deviation below the Mean Value. 1 knot = 1.151 mpg. 40 knots = 46 mph

Quartile Plot



The top blue dot-within-the-circle indicates the maximum value for the month. The top of the green bar indicates the value of 75th Percentile. The bottom blue dot-within-the-circle indicates the Minimum Value. The blue dot-within-the circle in the middle of the green bar indicates the Median or 50th Percentile. The bottom of the green bar indicates the value of the 25th Percentile. The tabulated data is presented on the following page along with gust data.

The data indicates that the prevailing wind speeds in general between 5 to 10 knots (8 to 15 mph), with 75% of the wind speeds being less than 15 knots (23 mph). Based on GZA's statistical analysis, the 1-year recurrence interval 1, 2-minute sustained wind speed (i.e., near 100% probability) is about 35 mph. The 5 to 10-year recurrence interval 1, 2-minute sustained wind speeds (i.e., +/- 20% to 10% probability) are about 55 to 60 mph.

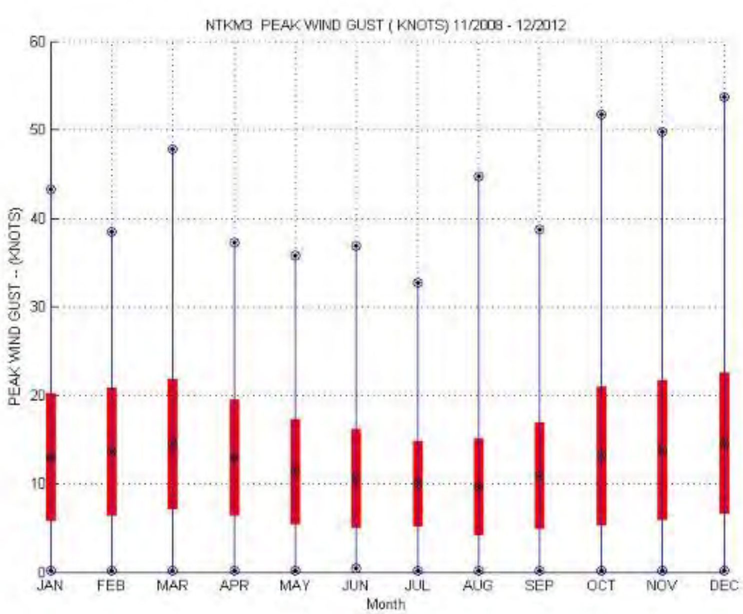
1 - MONTHLY AND ANNUAL FREQUENCY AND CUMULATIVE PERCENT FREQUENCY (10THS)

ELEMENT: AVERAGE WIND SPEED (KNOTS) -- POR: (11/2008 - 12/2012) (348583 RECORDS, 86.7% HAVE ELEMENT)

	JAN		FEB		MAR		APR		MAY		JUN		JUL		AUG		SEP		OCT		NOV		DEC		ANN	
	F	CPF	F	CPF	F	CPF	F	CPF	F	CPF	F	CPF	F	CPF	F	CPF	F	CPF	F	CPF	F	CPF	F	CPF	F	CPF
40	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	1	#	-	-	-	-	1	#
39	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	1	999	-	-	-	-	1	999
38	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	2	999	-	-	1	#	3	999
37	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0	999
36	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	8	999	3	#	3	999	14	999
35	-	-	-	-	1	#	-	-	-	-	-	-	-	-	-	-	-	-	10	999	3	999	6	999	20	999
34	1	#	-	-	1	999	-	-	-	-	-	-	-	-	-	-	-	-	4	999	6	999	9	999	21	999
33	1	999	-	-	6	999	-	-	-	-	-	-	-	-	2	#	-	-	10	999	8	999	6	999	33	999
32	-	-	-	-	8	999	-	-	-	-	-	-	-	-	3	999	-	-	11	999	6	999	12	999	40	999
31	1	999	-	-	8	999	-	-	-	-	-	-	-	-	-	-	-	-	16	998	20	999	10	999	55	999
30	4	999	-	-	12	999	-	-	-	-	-	-	-	-	2	999	-	-	22	998	23	999	16	999	79	999
29	2	999	-	-	13	999	-	-	-	-	-	-	-	-	3	999	-	-	26	997	24	998	30	998	98	999
28	5	999	-	-	14	998	-	-	-	-	-	-	-	-	-	-	-	-	26	996	25	997	25	997	95	999
27	16	999	3	#	24	998	6	#	-	-	-	-	-	-	-	-	3	#	35	995	30	996	46	997	163	999
26	29	999	3	999	36	997	7	999	-	-	4	#	-	-	2	999	7	999	62	994	43	996	59	995	252	998
25	24	998	15	999	43	995	6	999	6	#	2	999	-	-	5	999	6	999	69	992	41	994	53	994	270	997
24	36	997	14	999	55	994	9	999	8	999	7	999	-	-	5	999	5	999	77	989	68	993	79	992	363	997
23	48	996	25	999	89	991	17	999	14	999	8	999	-	-	9	999	14	999	100	987	104	991	116	990	544	996
22	73	994	43	998	149	988	34	998	36	999	9	999	3	#	22	999	11	999	116	983	144	988	138	987	778	994
21	73	992	80	996	162	982	57	997	54	998	16	999	3	999	42	998	20	998	154	979	207	984	193	983	1061	992
20	93	989	137	993	240	976	90	995	69	996	22	998	9	999	83	997	45	998	164	974	309	977	215	978	1476	989
19	146	986	251	988	351	966	136	991	102	994	53	998	10	999	126	994	73	996	271	968	470	968	421	972	2410	985
18	228	981	316	978	433	953	168	986	124	990	87	996	17	999	101	990	122	993	312	959	439	954	466	960	2813	978
17	309	973	354	966	517	936	226	980	126	986	83	993	24	999	100	986	189	989	354	948	539	941	682	947	3503	970
16	414	962	489	953	654	915	318	971	175	982	137	990	57	998	104	983	280	982	466	935	722	925	914	928	4730	960
15	637	947	593	934	773	890	440	959	225	976	218	985	89	996	101	979	390	971	644	919	857	903	1137	903	6104	946
14	798	925	834	912	929	860	650	942	318	968	319	977	135	993	183	976	534	957	803	896	1101	878	1374	871	7978	928
13	1026	897	1077	880	1147	823	971	917	478	957	496	966	238	988	226	970	651	937	994	868	1272	845	1714	833	10290	906
12	1594	861	1605	839	1669	779	1607	880	992	941	925	949	527	980	427	962	1037	913	1552	834	2072	807	2412	785	16419	876
11	1591	805	1701	778	1721	713	1739	818	1328	908	1128	917	752	962	617	947	1084	875	1556	779	1996	745	2229	718	17442	829
10	1882	750	2110	714	1896	646	1980	752	1964	863	1470	877	1295	937	1004	926	1486	834	1787	725	2492	685	2592	656	21958	779
9	2216	684	2275	633	2081	572	2194	676	2523	796	2074	826	2040	893	1493	892	1847	779	2079	662	2643	611	2890	584	26355	716
8	2501	606	2329	547	2335	491	2567	592	3237	711	2717	753	2749	824	2258	842	2425	711	2276	590	2866	532	3192	503	31452	640
7	2779	519	2336	458	2196	399	2727	494	3512	601	3110	658	3681	731	3115	765	2690	621	2488	510	2751	446	3067	414	34452	550
6	2760	421	2154	370	2150	313	2862	389	3361	482	3659	549	4276	606	3907	659	2868	522	2617	423	2593	364	2775	329	35982	451
5	3045	325	2367	288	2109	229	2794	280	3932	368	4523	421	5359	461	5255	526	3351	416	2794	331	2745	287	2694	252	40968	348
4	2231	218	1767	198	1297	147	1807	173	2767	235	3278	263	3768	279	4263	347	2895	292	2014	233	2156	205	1915	177	30158	231
3	1785	140	1473	131	1170	96	1289	104	2076	141	2271	149	2415	151	3471	202	2640	184	1968	163	1931	140	1719	124	24208	144
2	1277	77	1163	75	851	51	846	54	1339	71	1320	69	1317	69	1697	84	1566	87	1682	94	1503	83	1532	76	16093	75
1	770	33	658	31	367	17	480	22	605	26	563	23	603	25	642	26	651	29	831	35	1010	38	967	33	8147	28
0	158	6	149	6	75	3	91	3	150	5	98	3	129	4	134	5	122	5	178	6	250	7	220	6	1754	5
75PCTL		10.5		10.9		12.1		10.3		8.9		8.4		7.6		7.4		8.9		10.9		11.5		11.9		9.9
50PCTL		7.4		8.0		8.6		7.6		6.6		6.0		5.8		5.4		6.2		7.4		8.2		8.4		7.0
25PCTL		4.7		5.1		5.8		5.2		4.5		4.3		4.3		3.7		4.1		4.7		5.1		5.4		4.7
MEAN		7.9		8.3		9.2		8.0		7.0		6.6		6.1		5.9		6.9		8.2		8.7		9.0		7.7
S.D.		4.3		4.3		4.8		3.9		3.5		3.3		2.7		3.2		3.8		5.0		5.0		4.9		4.3
TOTAL		28553		26321		25582		26118		29521		28597		29496		29402		27012		28580		33472		35929		348583
MAX		34.0		27.2		34.8		27.2		25.1		26.0		22.0		33.4		27.0		39.9		36.4		38.3		39.9
DATE		2012011214		2010022523		2010031406		2011041310		2011050917		2009062215		2012073123		2010082313		2010090406		2012102919		2012110722		2012122709		2012102919
MIN		0.2		0.2		0.2		0.2		0.2		0.2		0.2		0.2		0.2		0.2		0.2		0.2		0.2
DATE		2012013107		2012022911		2012031104		2012041908		2012053110		2012062608		2012072212		2012082706		2012091712		2012102711		2012112715		2012122913		2012122913

(* < 0.05% , # = 100.0%)

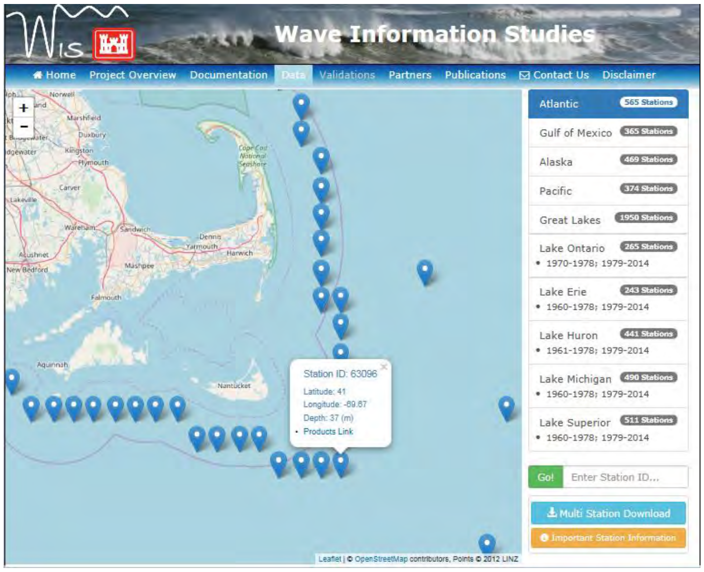
Mean and Standard Deviation Plot

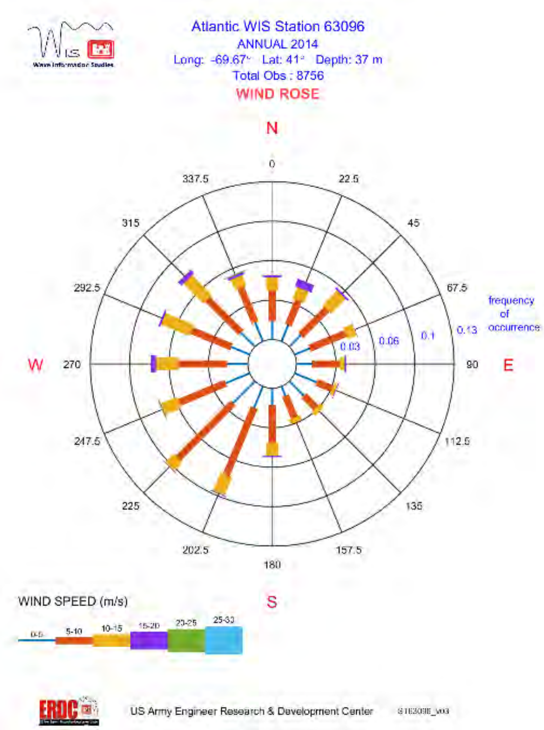


The top blue dot-within-the-circle indicates the maximum value for the month. The top of the red bar indicates the value of one (1) Standard Deviation above the Mean Value. The bottom blue dot-within-the-circle indicates the Minimum Value. The blue dot-within-the circle in the middle of the red bar indicates the Mean or Average value. The bottom of the red bar indicates the value one (1) Standard Deviation below the Mean Value. 1 knot = 1.151 mpg. 55 knots = 64 mph

USACE Wave Information Studies - Prevailing Ocean Wind Direction

The USACE WIS data presents an annual wind rose for the year 2014. The data, presented below, indicates that elevated sustained wind speeds (15 to 20 m/s [33 to 45 mph]) come from the west to east and predominantly from the northeast - consistent with the occurrence of nor'easters.





ATLANTIC HINDCAST WAM4.5.1C : ST63096_v03
ALL MONTHS: FOR YEAR PROCESSED : 2014
STATION LOCATION : (-69.67 W / 41.00 N)
DEPTH : 37.0 m

PERCENT OCCURRENCE (X1000) OF WIND SPEED AND DIRECTION
CENTRAL LOCAL ANGLE BANDS OF (+/- 11.25 DEG)

NO. CASES : 8756

WND DIR DEG	WIND SPEED (M/S) <2.5	2.5-4.9	5.0-7.4	7.5-9.9	10.0-12.4	12.5-14.9	15.0-17.4	17.5-19.9	20.0-24.9	25.0-GREATER	TOTAL
0.0	171	1233	1427	1130	685	468	22	137	34	11	5318
22.5	148	1267	1062	1153	879	137	354	285	11	0	5296
45.0	182	1084	1667	1370	1256	479	114	57	0	0	6209
67.5	239	1050	1633	1587	673	171	22	0	0	0	5375
90.0	194	1027	1279	1050	182	228	79	68	0	0	4107
112.5	159	1621	970	571	262	57	34	22	0	0	3696
135.0	148	1484	856	559	331	159	0	0	0	0	3537
157.5	102	719	1073	845	365	91	0	0	0	0	3195
180.0	171	1119	1930	1244	856	216	137	0	0	0	5673
202.5	205	1473	3483	2592	1484	274	68	0	0	0	9579
225.0	205	2249	3677	2775	947	102	11	11	22	0	9999
247.5	171	1838	2192	2010	867	639	22	22	79	0	7840
270.0	114	1530	2295	1747	1096	788	296	137	0	0	8003
292.5	102	1518	1553	1918	1553	1050	91	79	0	0	7864
315.0	194	1427	1576	2295	1301	1016	262	125	57	0	8253
337.5	171	1450	1598	1541	765	171	91	102	68	34	5991
TOTAL	2676	22089	28271	24387	13502	6046	1603	1045	271	45	

MEAN WS(M/S) = 7.6 MAX WS(M/S) = 25.9 MEAN WIND DIR(DEG) = 97.0 FINITE

Correlation of Wind Speed and Water Level

The correlation between: 1) top peak wind speeds and associated water levels; and 2) top peak water levels and associated wind speeds was performed.

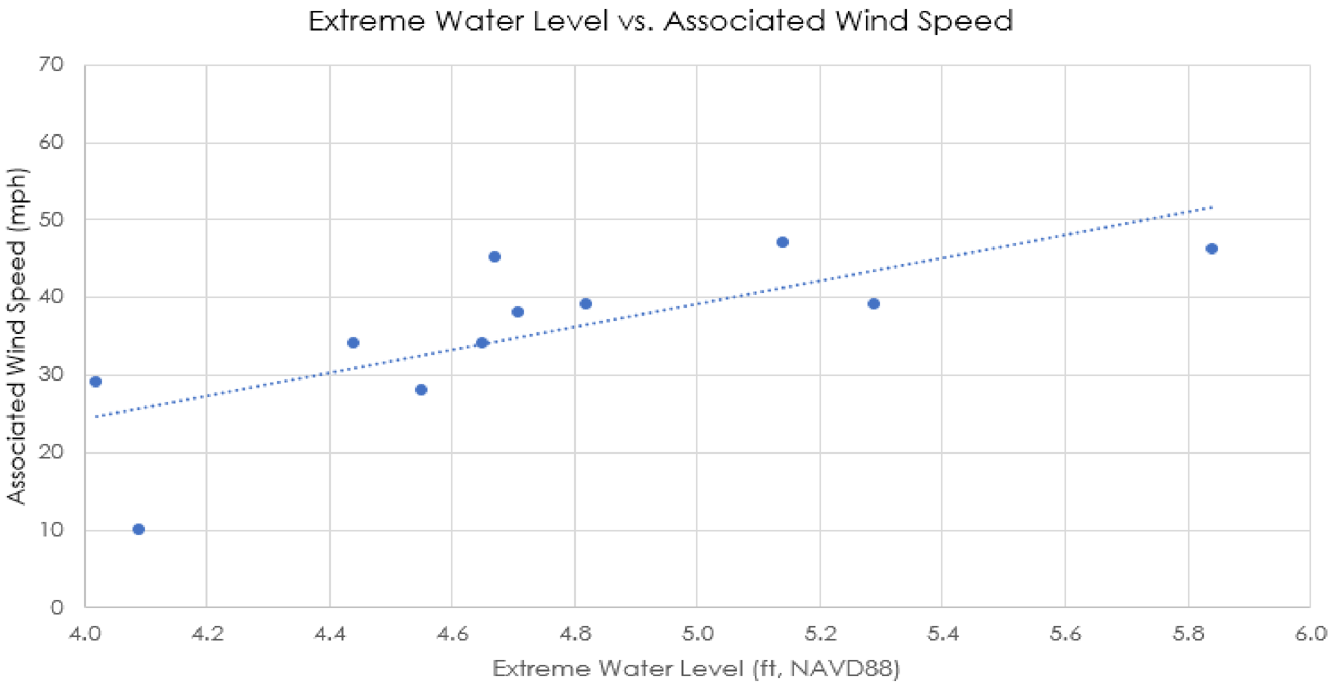


Figure 9: Comparison of Elevated Water Levels at Nantucket NOAA Tidal Station and associated Wind Speeds at Nantucket Airport

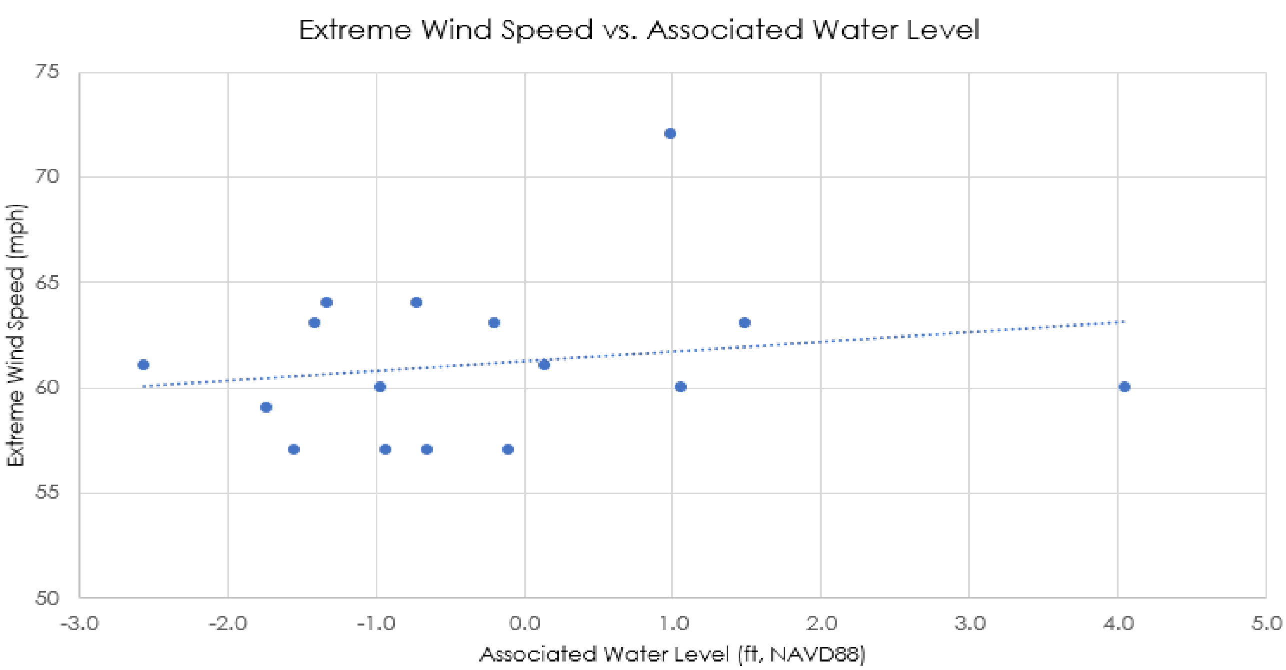


Figure 10: Comparison of Elevated Wind Speeds at Nantucket Airport and associated Water Levels at NOAA Tidal Station

Discussion

GZA completed an evaluation of available wind data for the purpose of establishing design basis environmental loads for design of the Town Pier. The evaluation considered: 1) wind intensity-frequency relationships up to the 100-year recurrence interval frequency; 2) wind directionality effects on intensity; and 3) prevailing (i.e., typical wind conditions representative of about 75% of the winds experienced at Nantucket). Multiple data sources were evaluated including: ASCE 7-10 prescriptive 3-second gust wind speeds; 2) Nantucket Airport data (71 - year record); 3) NOAA Nantucket Land Station (5-year record); 4) USACE Wave Information Studies ocean wind data; and 4) GZA Metocean Data and Modeling Program (GZA MDMP) tropical cyclone data.

Based on GEV statistical analysis of the 71-year wind record at Nantucket Airport, the largest magnitude wind speeds are predicted from the South quadrant (135° to 225° in degrees clockwise from north). The predicted 100-year mean recurrence interval 1 and/or 2-minute sustained wind velocity at 10 meters from the South is about 80 mph. The predicted 100-year mean recurrence interval, 1 and/or 2-minute sustained wind velocity aligned with the harbor fetch (North to East quadrant) is about 70 mph. The predicted 100-year mean recurrence interval all-direction 1 and/or 2-minute sustained wind velocity is about 70 mph.

There is a significant difference between ASCE/SEI 7-10-derived wind speeds and wind speeds developed based on statistical analysis of Nantucket airport data. There are several potential reasons for this difference. The ASCE/SEI 7-10 wind speeds at Nantucket (a hurricane-prone region) were developed utilizing synthetic tropical cyclone storm tracks and are consistent with the occurrence of hurricanes. The ASCE/SEI data matches well with GZA's MDMP At-Sea distributions of HURDAT2 historical hurricane maximum wind speeds. The Nantucket Airport wind record (peak winds) appears to consist predominantly of extratropical nor'easter storms with occasional short duration events (thunderstorms) and minimal hurricane events. Both ASCE/SEI 7-10 and Nantucket Airport data are valid for use on this project, with greater conservatism associated with ASCE/SEI 7-10 (in particular considering the low probability of a hurricane striking Nantucket or bypassing to the south and east of the island as required to establish winds from the East-Northeast within Nantucket Harbor).

The data indicates that the prevailing wind speeds in Nantucket, in general between 5 to 10 knots (8 to 15 mph), with 75% of the wind speeds being less than 15 knots (23 mph). Based on GZA's statistical analysis, the 1-year recurrence interval 1, 2-minute sustained wind speed (i.e., near 100% probability) is about 35 mph. The 5 to 10-year recurrence interval 1, 2-minute sustained wind speeds (i.e., +/- 20% to 10% probability) are about 55 to 60 mph.

The following presents wind data for recent, significant wind events, for experiential reference to the statistical data:

- October 30, 1991 The Perfect Storm (large wave and storm surge event): Maximum 1,2 – minute sustained winds at Nantucket +/- 50 mph
- January 27, 2015 nor'easter: Maximum 1,2-minute sustained winds at Nantucket +/- 50 mph (maximum 3-sec gust +/- 60 mph)
- January 4, 2018 nor'easter: Maximum 1,2- minute sustained winds at Nantucket +/- 35 mph (maximum 3-sec gust +/- 50 mph)
- March 3-4, 2018 nor'easter: Maximum 1,2- minute sustained winds at Nantucket +/- 40 mph (maximum 3-sec gust +/- 55 mph)
- February 9, 2013 nor'easter: Maximum 1,2- minute sustained winds at Nantucket +/- 50 mph (maximum 3-sec gust +/- 60 mph)

Comparison of peak wind and water levels indicates:

1. Peak water levels (storm surge) at Nantucket are relatively well-correlated with elevated wind speeds (meaning that the storms generating these surges also produce elevated winds near and over the island.
2. Elevated wind speed events can occur over a wide range of water levels, meaning that a severe wind event within Nantucket Harbor could occur coincident with a range of water levels from normal tides to storm surge.
3. The relevance of these comparisons indicates that: a) it is reasonable to assume coincident elevated water levels and wind speeds (e.g., simulating a 100-year recurrence interval wind speed with a 100-year recurrence interval water level); and b) the analysis of the Town Pier should conservatively consider a wide range of water levels coincident with elevated wind speeds.

Climate Change Effects

Although data about attribution of wind intensity to climate change is limited and of low confidence, there are several potential factors that could affect Nantucket wind frequency:

- The occurrence and frequency of New England nor'easters is related to the Jet Stream, in turn related to La Nina conditions in the equatorial Pacific. La Nina conditions have not yet been correlated to climate change; however, in conjunction with climate change-induced warming ocean temperatures (an increased atmospheric moisture) may result in increased intensity of nor'easters and greater snowfall.

- The warming Arctic may have implications for the frequency and intensity of New England nor'easters, due to the temperature gradient between the Arctic and the warmer southern temperatures will affect the Jet Stream and prevailing wind intensities. This temperature gradient may also affect (disorganize) the polar vortex (an Arctic low pressures system), that can result in cold New England air temperatures.

- Relative to the historical record, the multiple intense nor'easters that occurred during the 2018 season was an unusual event. GZA MDMP analysis indicates that the probability of experiencing the 2018 combined storm conditions (in Boston) was about 1/7,500 – a rare event. The year 2018 was a record warming La Nina event.

- Per Climate.gov, the National Climate Assessment notes that for the entire Northern Hemisphere, there has been an increase in both the number and strength of storms during colder months since 1950. And, in particular, extremely heavy snowstorms have increased in number over the last century in northern and eastern parts of the United States. Though, these types of extreme events have been less frequent since 2000.

- The attribution of climate change and North West Atlantic hurricane frequency is also not well developed, and of low confidence. However, the increasing sea temperatures may result in a poleward advancement of the intensity of hurricanes.

The implication of these climate change effects on the Nantucket wind intensity-frequency relationship are: 1) the potential for an increase in the frequency of nor'easters, in particular coincident with La Nina events; and 2) the increased intensity of hurricanes that may occur within the Nantucket strike zone. Each of these conditions, were they to occur, would be expected to shift the wind intensity-frequency curve upward and to the right.

However, within the climate change industry the attribution confidence level, at this time, for this condition to occur is low. Also, these effects are likely captured within the current wind intensity uncertainty bounds. Therefore, it is not recommended that climate change effects on wind intensity be a design consideration for the Town Pier. Climate change effects associated with sea level rise should be considered.

ATTACHMENT 5
Extreme Water Levels

Extreme Water Levels

Coastal flooding at the Town Pier occurs due to storm surge within Nantucket Sound, creating elevated water levels within the Nantucket Harbor Estuary. Coastal flooding includes several components:

1. Storm surge, which is the water height that results from water being pushed toward the shore by strong winds during a storm. The height of the storm surge is affected by many variables, including storm intensity, storm track and speed, the presence of waves, offshore depths, and shoreline configuration. When combined with tides, the storm surge is referred to as the storm tide. This rise in water level can cause severe flooding in coastal areas, particularly when the storm coincides with high tides.
2. Stillwater elevation, which is the projected elevation of floodwaters (storm tide) in the absence of wave effects.
3. Wind-generated waves, which can occur coincident with storm surge and are characterized by:
   - Wave height (vertical distance from trough to crest)
   - Wave length (distance from crest to crest in the direction of propagation)
   - Wave period (time interval between arrival of consecutive crests at a stationary point)
   - Wave propagation direction
4. Significant wave height (H_s) represents the average height of the highest one-third of the waves in a given time period (usually chosen somewhere in the range from 20 minutes to twelve hours), or in a specific wave or storm system. Other wave statistics are relevant to design of the Town Pier. These include (assuming a Rayleigh wave distribution): 1) $H_{1/10} = H_s \times 1.27$; 2) $H_{1/100} = H_s \times 1.67$; and 3) $H_{1/1000} = +/- H_{max} = +/- H_s \times 2$.
5. Wave setup, which is the increase in the water level caused by the onshore mass transport of water that happens due to waves breaking during a storm. Wave setup is affected by the wave height, the speed at which waves approach the shore, and the slope of the shore.
6. Total water level, which includes the stillwater level plus wave setup.
7. Wave crest elevation, which is the elevation of the top of the wave crest. The portion of the wave occurring above the total water (or stillwater) level is dependent upon the wave characteristics and shoaling effects. For depth-limited waves, about 70% of the wave height is above the stillwater level.

An assessment of the coastal flood frequency applicable to the Town Pier was performed based on the following data sources. Flood frequency is characterized in terms of recurrence interval (and annual exceedance probability).

- GZA performed a statistical analysis of the NOAA Nantucket Tide Station monthly and annually maximum water level data using Generalized Extreme Value (GEV) statistics.
- The results of the Army Corps of Engineers (USACE) North Atlantic Coast Comprehensive Study (NAACS). This study was performed by the USACE after Hurricane Sandy to characterize coastal flood hazards in areas impacted by Hurricane Sandy (from the Chesapeake Bay to New Hampshire). The study included statistical analysis and computer modeling of storm surge and waves. The study provides nearshore storm surge and wave hazard data at multiple locations around Nantucket.
- The current FEMA FIRMs and Flood Insurance Studies (FIS). The current FEMA FIS is the Nantucket County, Massachusetts study, effective date June 9, 2014, Flood Insurance Study Number 25019CV000A.

Nantucket Tide Station

The NOAA Nantucket Station 8449130 was established in 1963 (55 year record). The annual maximum water levels observed at the station during time period (corrected for observed sea level) are presented in **Figure 1**. The calculated mean flood-frequency curve based on monthly maximums are presented in **Figure 2**. The calculated mean flood frequency curve based on annual maximums are presented in **Figure 3**.

The Mean Higher-High Water (MHHW) and the Mean Lower-Low Water (MLLW) tide elevations for the current tidal epoch are Elevations 1.48 and -2.09 feet NAVD88, respectively. The mean range of tide is 3.04 feet. The Highest Astronomical Tide (HAT) is 2.32 feet NAVD88. During the period of record, the highest observed water level at the station was Elevation 5.78 feet NAVD88 reflecting the observed storm tide which occurred on October 30, 1991 (The 1991 Perfect Storm, also known as the “No-Name” Storm and the Halloween Gale).

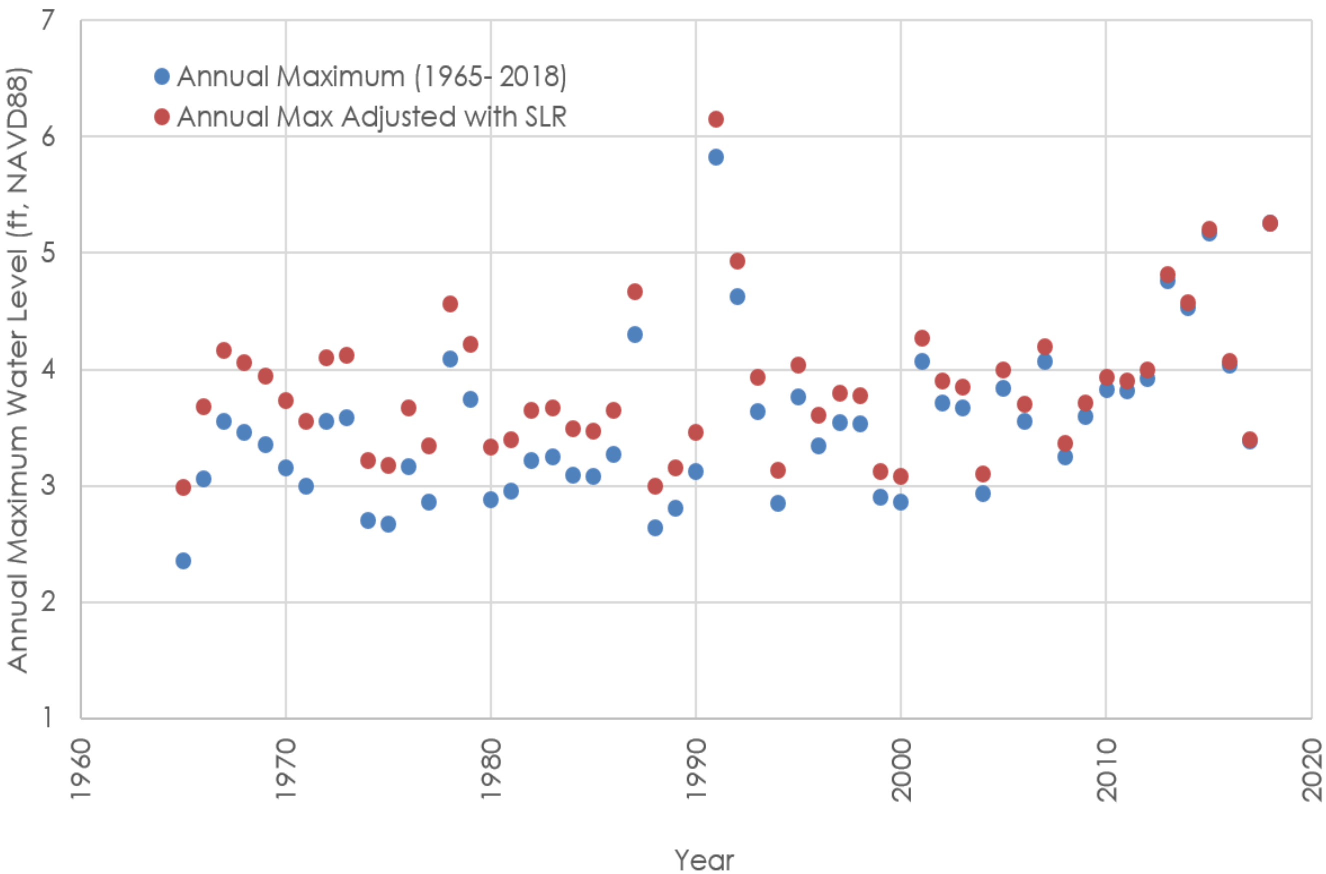


Figure 1: Annual Maximum Water Levels observed at NOAA Tidal Station 8449130 at Nantucket (feet, NAVD88)

Figure 2: Flood-Frequency Curve developed by GZA based on Maximum Monthly Water Levels observed at NOAA Tidal Station 8449130 at Nantucket (feet, NAVD88)

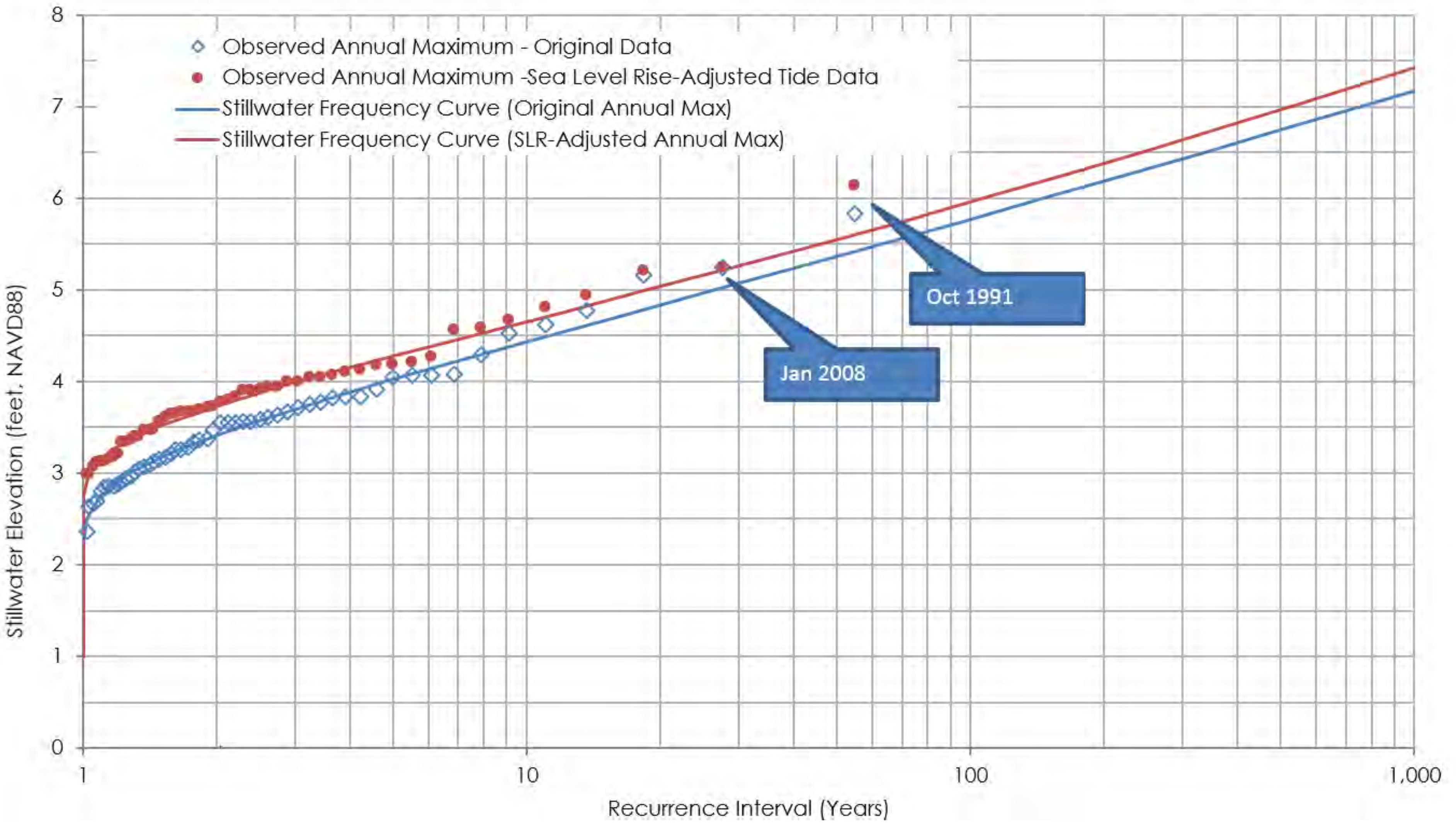


Figure 3: Flood-Frequency Curve developed by GZA based on Maximum Annual Water Levels observed at NOAA Tidal Station 8449130 at Nantucket (feet, NAVD88)

USACE NACCS

The USACE North Atlantic Coast Comprehensive Study developed flood elevations and wave heights for the U.S. North Atlantic coast (Chesapeake Bay to New Hampshire) using numerical storm surge and wave modeling (ADCIRC+STWAVE) and the Joint Probability Method (JPM) and Empirical Simulation Technique (EST) statistical methodology. The NACCS provides storm surge water levels and wind-generated waves corresponding to different probability recurrence intervals at established "save points". Save Points 7380 and 9187 are in the vicinity of the Nantucket Town Pier. Save point 10082, 9186 and 9185 are located within the Nantucket Harbor. Flood-frequency curves for these save points are presented below.

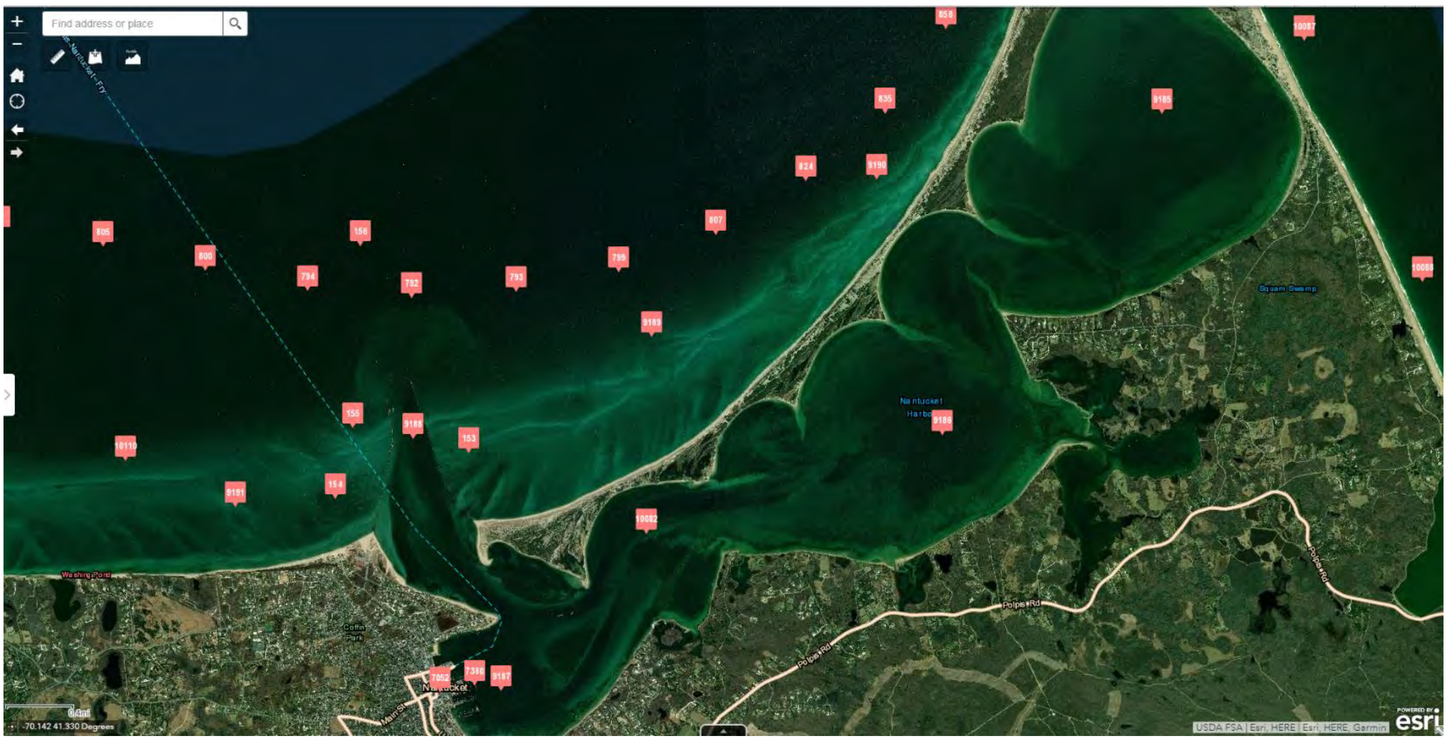


Figure 4: USACE North Atlantic Coast Comprehensive Study Save Point Locations near the Town Pier

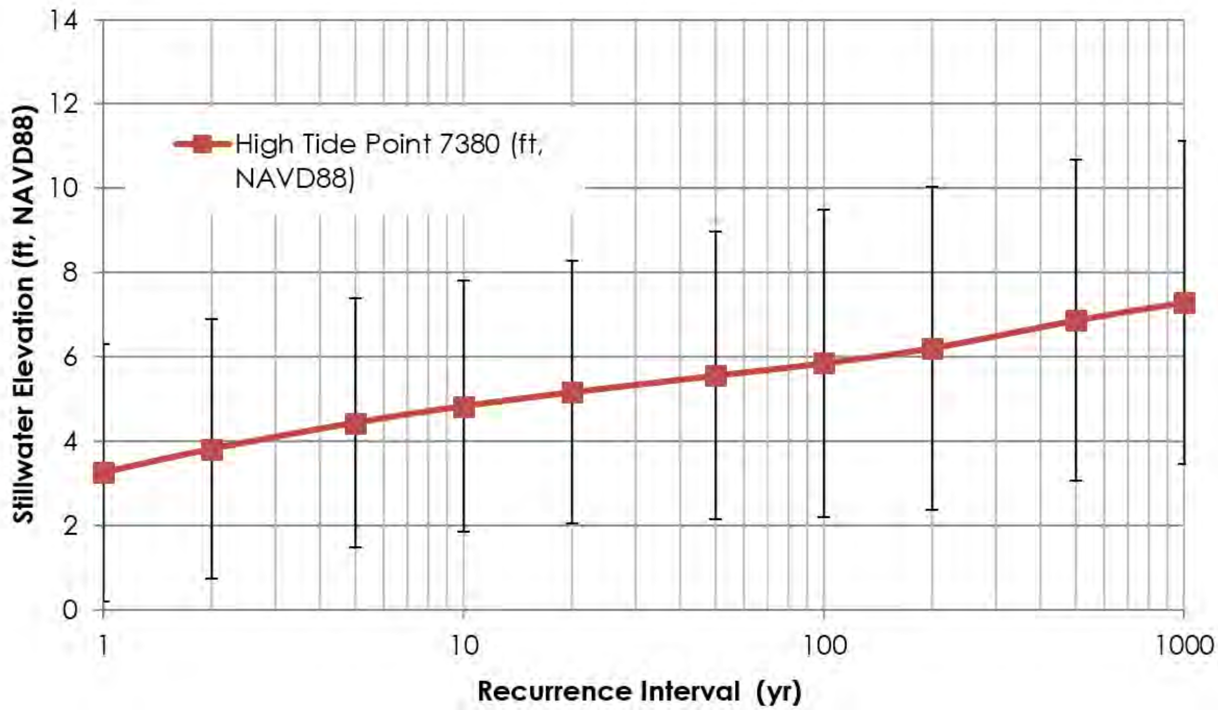


Figure 5: Flood Frequency Curve developed for USACE North Atlantic Coast Comprehensive Study at Save Point 7380 (feet, NAVD88)

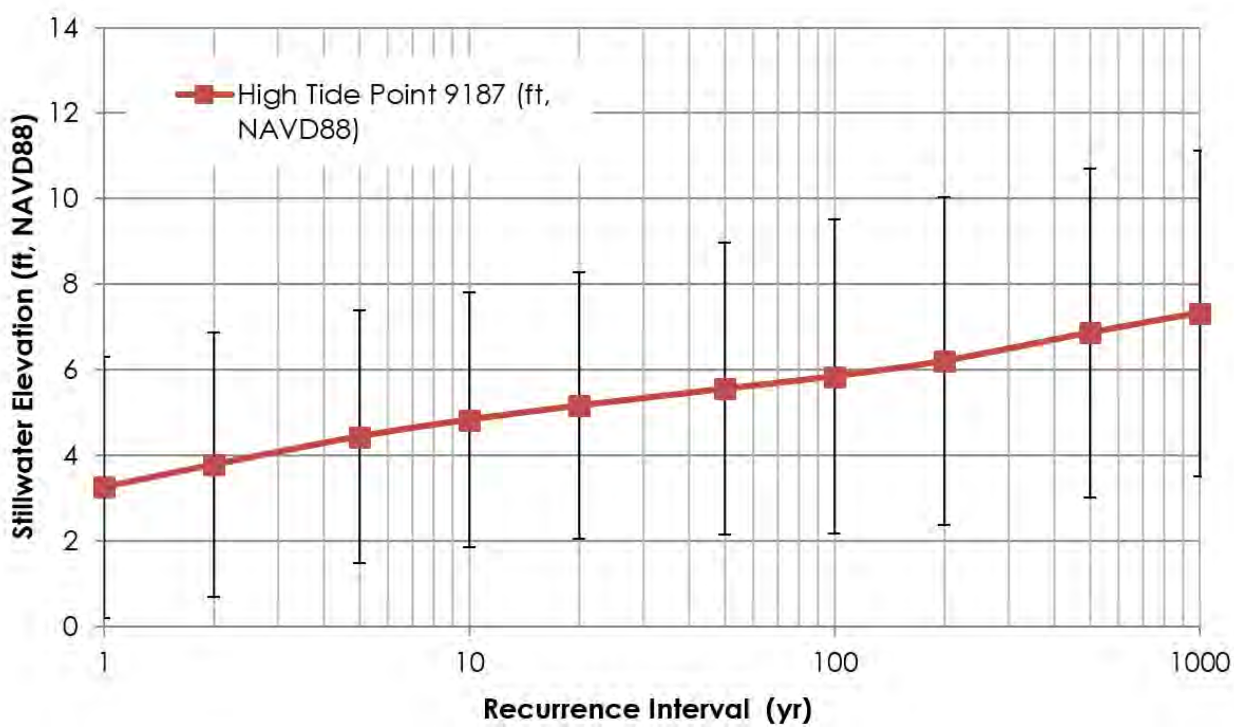


Figure 6: Flood Frequency Curve developed for USACE North Atlantic Coast Comprehensive Study at Save Point 9187 (feet, NAVD88)

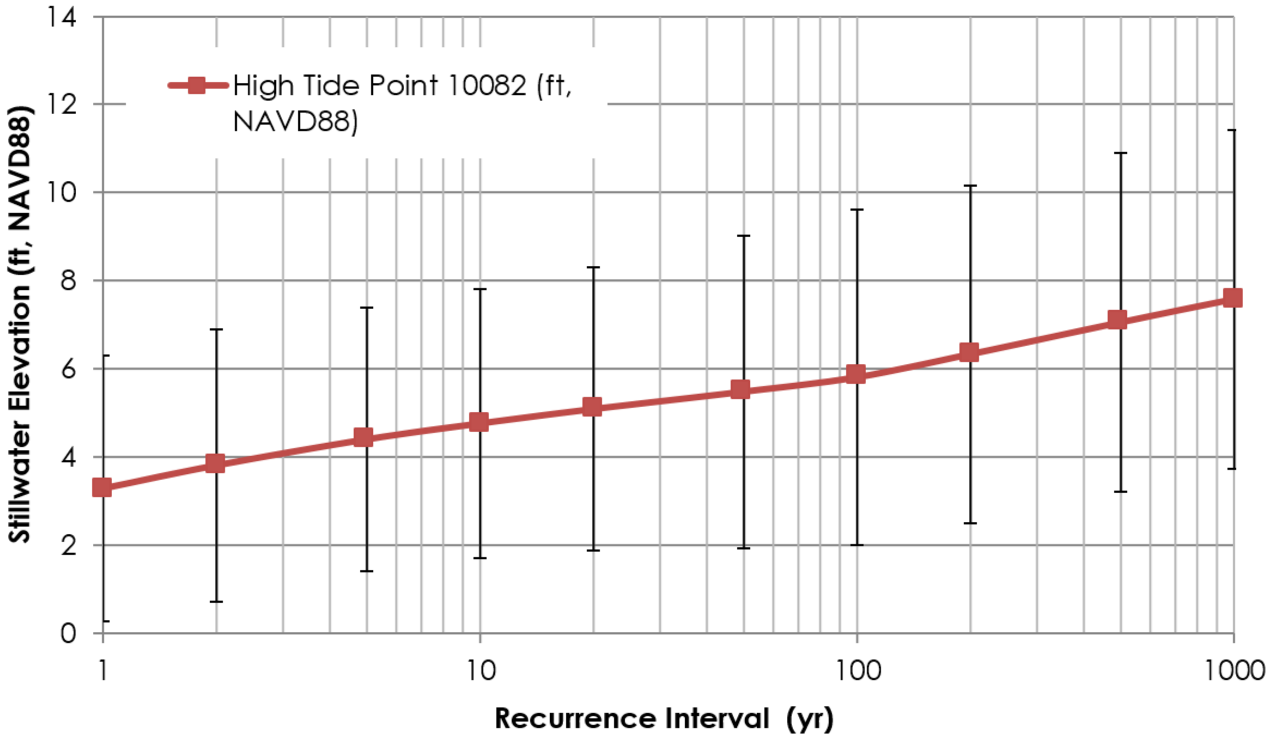


Figure 7: Flood Frequency Curve developed for USACE North Atlantic Coast Comprehensive Study at Save Point 10082 (feet, NAVD88)

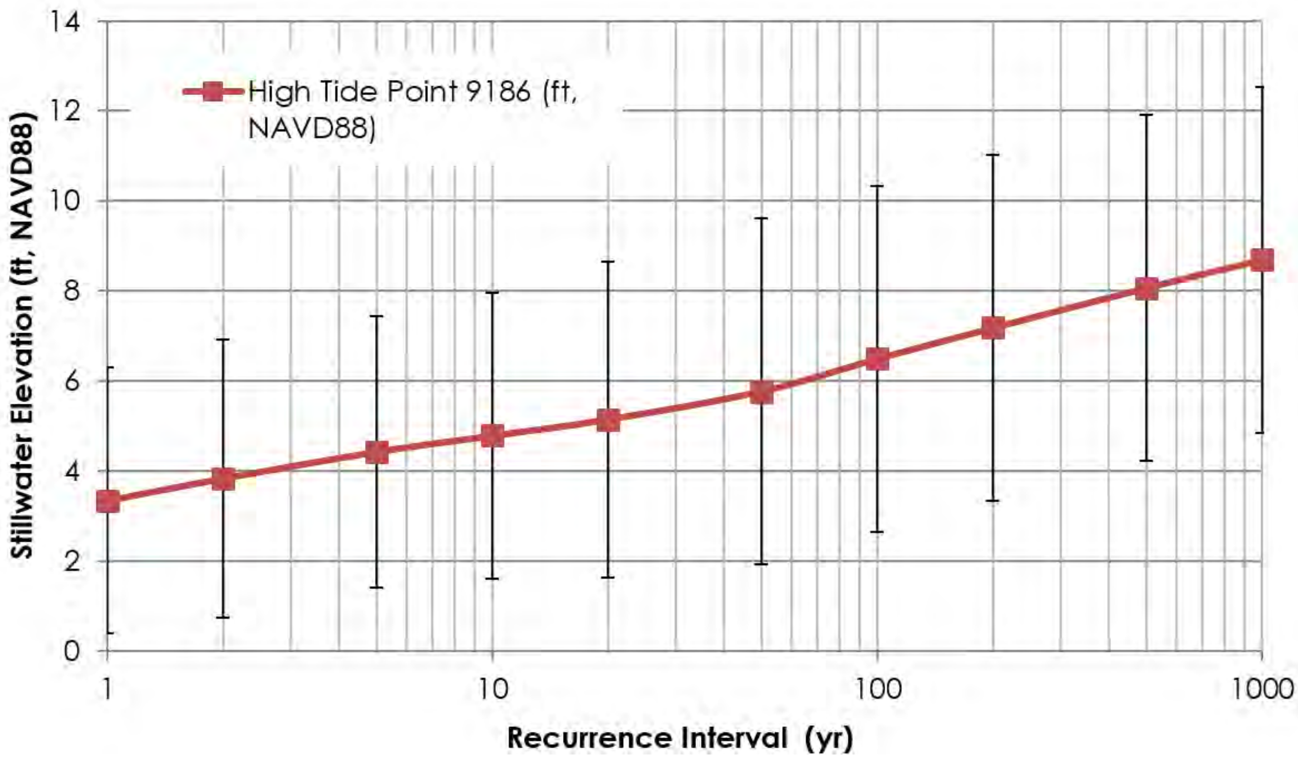


Figure 8: Flood Frequency Curve developed for USACE North Atlantic Coast Comprehensive Study at Save Point 9186 (feet, NAVD88)

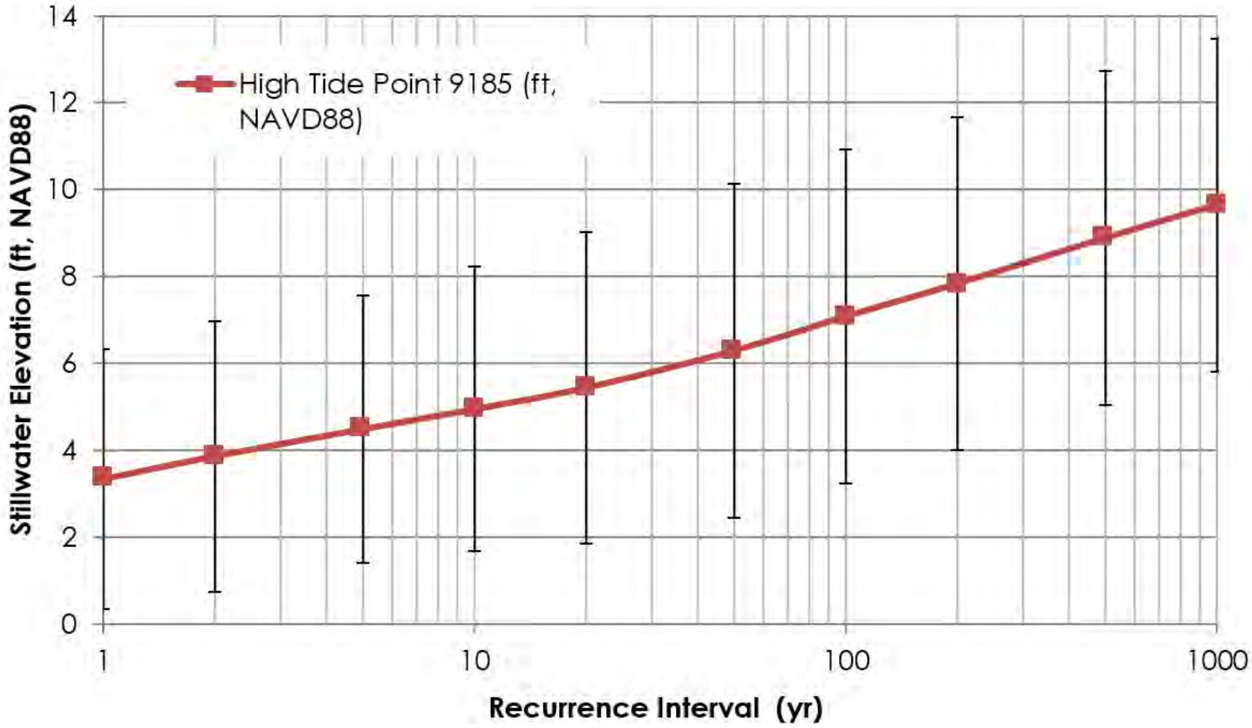


Figure 9: Flood Frequency Curve developed for USACE North Atlantic Coast Comprehensive Study at Save Point 9185 (feet, NAVD88)

FEMA Flood Hazard Determination

Through FEMA's flood hazard mapping program, Risk Mapping, Assessment and Planning (MAP), FEMA identifies flood hazards, assesses flood risks and partners with states and communities to provide accurate flood hazard and risk data to guide them to mitigation actions. Flood hazard mapping is an important part of the National Flood Insurance Program (NFIP), as it is the basis of the NFIP regulations and flood insurance requirements. FEMA maintains and updates data through Flood Insurance Rate Maps (FIRMs) and risk assessments. FEMA coastal transects provide detailed flood data at Nantucket. Flood elevations are presented in **Table 1** for: 1) the stillwater elevation, which is the water level in the absence of waves; 2) the Total Water Level which includes the stillwater elevation and the effects of wave setup; and 3) the Base Flood Elevation (BFE). The BFE is the flood having a one percent chance of being equaled or exceeded in any given year. This is the regulatory standard also referred to as the "100-year flood" and includes the Total Water Level plus wave plus wave runup. The elevation datum is feet, NAVD88. Transect 25 applies to the Town Pier.

The 100-year recurrence interval (1% annual exceedance probability) SWEL developed by FEMA for the vicinity of the Town Pier (Transect 25) is Elevation 6.1 feet NAVD88. According to the FEMA FIS, the stillwater elevation was developed based on statistical extrapolation of tide gage data. Neither the FEMA FIRM nor FIS indicate the wave height and wave set-up used by FEMA in establishing the BFEs at the proposed pier. The FEMA FIS indicates that the 100-year recurrence interval total water elevation (including stillwater and wave setup) at Transect 25 is Elevation 8.8 feet NAVD88, indicating a predicted wave setup of about 2.7 feet. Total and stillwater elevations for other return periods are summarized on **Table 1.** The 100-year recurrence interval maximum wave crest elevation is 15 feet NAVD88. The BFE is Elevation 11 feet NAVD88.

Figure10: Effective (2012) FEMA Flood Insurance Rate Map Flood Hazard Zones. Base Flood Elevation near Town Pier is Elevation 11 feet, NAVD88

Flooding Source and Transect Number	Stillwater Elevation[3]				Total Water Level[1,3]		Base Flood Elevation (Feet NAVD 88)[2,3]
	10-percent-annual-chance	2-percent-annual-chance	1-percent-annual-chance	0.2-percent-annual-chance	1-percent-annual-chance	Zone	
ATLANTIC OCEAN - continued							
Town of Nantucket - continued							
Transect 13	3.4	4.8	5.8	8.1	7.4	VE	10
						AE	*
Transect 14	3.4	4.8	5.8	8.1	7.5	VE	10
						AE	*
Transect 15	3.4	4.8	5.8	8.1	7.4	VE	9-10
						AE	9
NANTUCKET HARBOR							
Town of Nantucket							
Transect 16	3.4	4.8	5.8	8.1	7.0	VE	9
						AE	7-8
Transect 17	3.6	5.1	6.1	8.6	7.3	VE	9
						AE	*
Transect 18	3.6	5.1	6.1	8.6	7.5	VE	9-10
						AE	*
Transect 19	3.6	5.1	6.1	8.6	7.3	VE	9-10
						AE	7-9
Transect 20	3.6	5.1	6.1	8.6	7.6	VE	12
						AE	*
Transect 21	3.6	5.1	6.1	8.6	7.3	VE	9
						AE	8-9
Transect 22	3.6	5.1	6.1	8.6	7.8	VE	11
						AE	8
Transect 23	3.6	5.1	6.1	8.6	7.3	VE	9
						AE	7-8
Transect 24	3.6	5.1	6.1	8.6	7.7	VE	10
						AE	8-9
Transect 25	3.6	5.1	6.1	8.6	8.8	VE	11
						AE	9-10
Transect 26	3.6	5.1	6.1	8.6	7.5	VE	10
						AE	8
Transect 27	3.6	5.1	6.1	8.6	7.3	VE	9
						AE	7-9

[1] Including stillwater elevation and effects of wave setup.
[2] Base flood elevations shown on the FIRM represent average elevations for the zones depicted.
[3] North American Vertical Datum of 1988 (NAVD 88).
*No Data Available

Table 1: Effective FEMA Insurance Study (FIS) Water Levels at Transect Locations. Transect 25 applies to the Town Pier.

Comparison of Extreme Water Levels

A comparison of the predicted water level data from the three data sources is presented on the mean flood-frequency curve in **Figure 11** (bars represent USACE NACCS 90% confidence bounds).

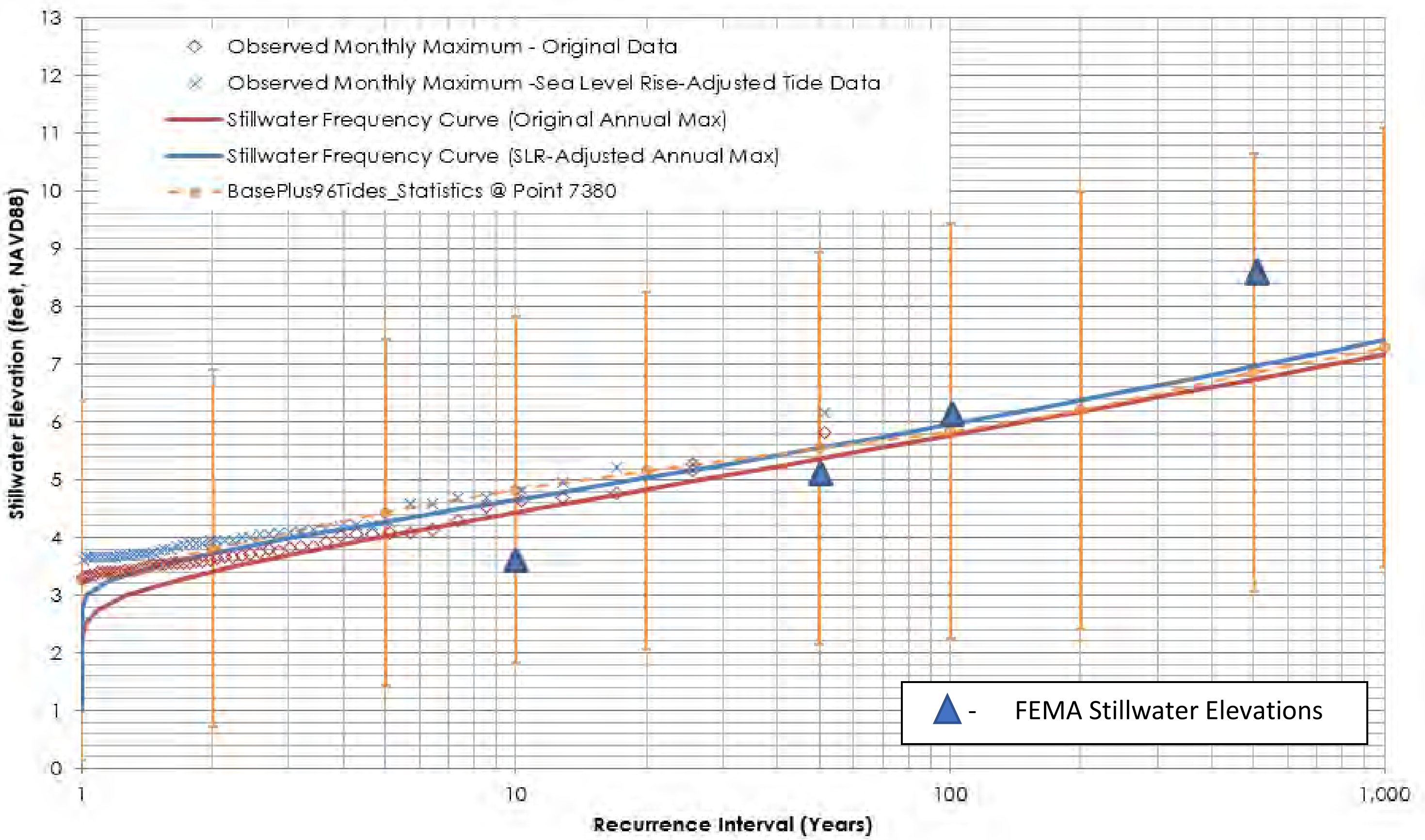


Figure 11: Combined Stillwater Flood-Frequency Data from Multiple Data Sources

Data Source	Mean Stillwater Elevation (SWEL)					
	1 yr	**10 yr**	**20 yr**	**50 yr**	**100 yr**	**500 yr**
USACE NACCS						
7380	3.3	4.8	5.2	5.6	5.8	6.9
9187	3.3	4.8	5.2	5.5	5.8	6.9
10082	3.3	4.8	5.1	5.5	5.8	7.1
9186	3.3	4.8	5.1	5.8	6.5	8.1
9185	3.3	4.9	5.4	6.3	7.1	8.9
NOAA Tide Station						
	3.6	4.6	5.0	5.6	6.0	7.0
FEMA Transect 25						
8683	-	3.6	-	5.1	6.1	8.6

Table 2: Combined Stillwater Flood-Frequency Data from Multiple Data Sources

In general, the three data sources result in similar mean flood-frequency predictions at the Town Pier. Two of the sources (FEMA and the GZA Nantucket Tide Station analysis) were developed based on statistical interpretation of historic wind (Nantucket Airport) and water level data over a limited time period. The USACE NACCS data was developed based on statistical interpolation of numerical simulations of historic extratropical storm tracks and synthetic tropical cyclone storm tracks.

The FEMA Total Water Level data for transect 25 indicates an estimated wave setup of 2.7 feet. Based on: 1) wave heights and breaking characteristics predicted by GZA; and 2) location of the Town Pier structure seaward of the Mean Sea Level Line (wave setup is generally a contributor to total water level landward of the +/- MSL line), this wave setup value appears to be excessive for use in the Town Pier design. Wave setup on the order of 15% of the wave height or less is recommended in the vicinity of the Town Pier.

Effects of Climate Change

The principal effect of climate change, with the greatest attribution confidence, is sea level rise. Sea Level Rise (SLR) is the rise of global ocean waters. Relative Sea Level Change (RSLC) is the change in sea level relative to the adjacent land mass and is unique to a given geographic location. RSLC is caused by several factors, including: 1) ground settlement due to post-glacial isostatic adjustment; 2) warming of ocean waters, resulting in volume expansion; 3) increase in ocean volumes due to melting Arctic and land ice; 4) ocean density gradients due to the infusion of lower density fresh water; and 5) changes to global ocean circulation patterns (e.g., the Gulf Stream and Labrador Current).

As shown in **Figure 12,** the observed RSLC at the NOAA Nantucket tide station, since 1963, indicates a mean sea level rise trend of 3.63 millimeters (mm) per year (with a 95% confidence interval of +/- 0.36 mm per year) (3.63 mm/yr = 0.143 inch/year; about 0.7-foot since 1963).

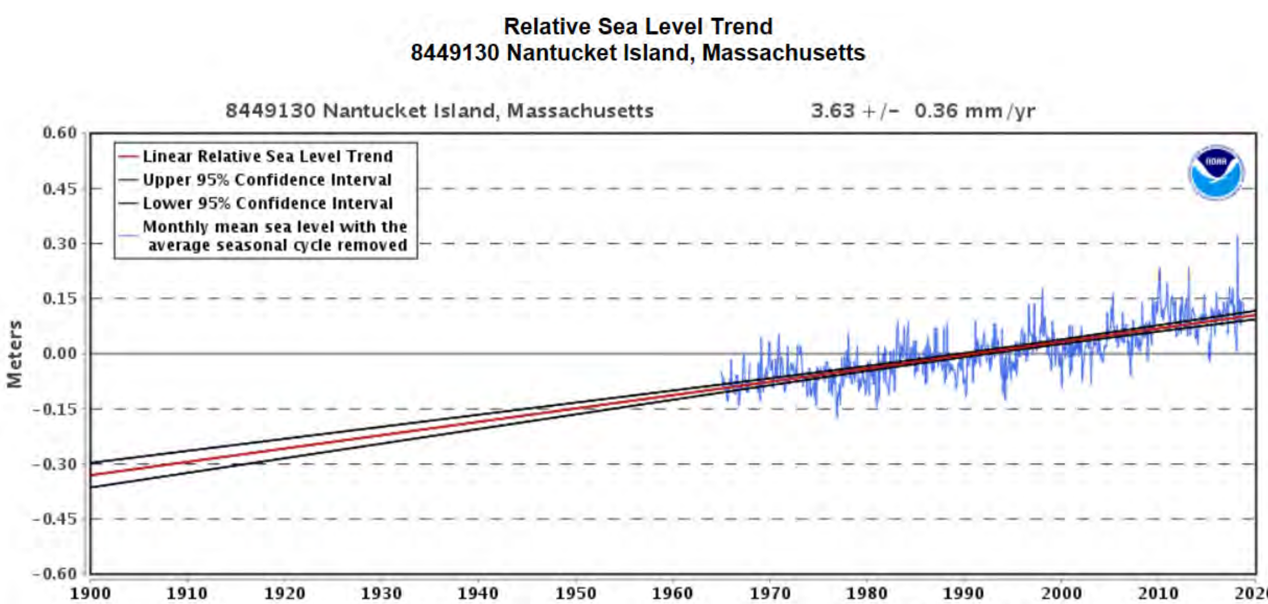


Figure 12: Observed Sea Level Rise Trends at NOAA Nantucket Tide Gage

NOAA and the USACE have developed ranges of RSLC for NOAA tide stations around the United States**. Figure 13** and **Table 3** present six NOAA 2017 projections for several possible future climate scenarios (Representative Concentration Pathways RCP 2.6, RCP 4.5, RCP 8.5) adopted by the Intergovernmental Panel on Climate Change (IPCC) for its fifth Assessment Report (AR5). In general, the median "Intermediate-Low" is considered appropriate as an "analysis and planning lower bound" and either the median "Intermediate" or median "Intermediate-High" is appropriate as an "analysis and planning upper bound". **Table 4** presents estimated exceedance probabilities associated with the six NOAA 2017 projections for several possible future climate scenarios (Representative Concentration Pathways RCP 2.6, RCP 4.5, RCP 8.5) adopted by the Intergovernmental Panel on Climate Change (IPCC) for its fifth Assessment Report (AR5).

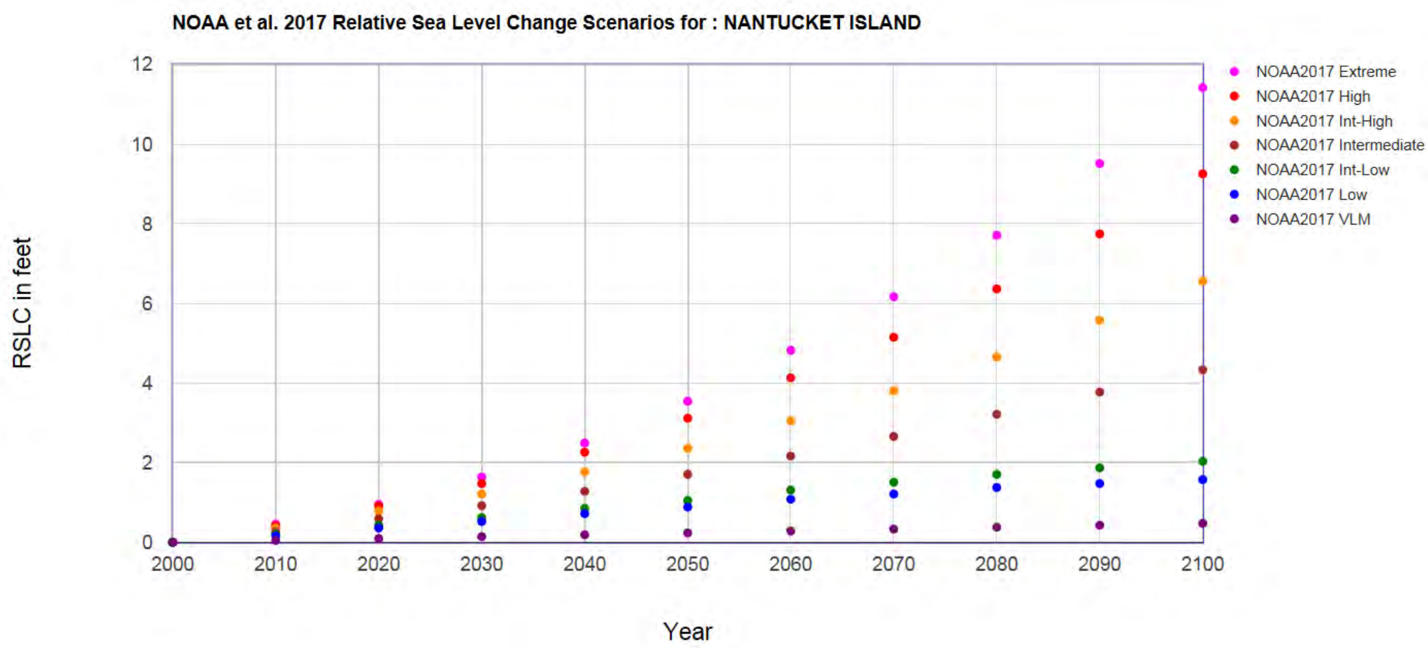


Figure 13: Predicted Relative Sea Level Rise Projections at NOAA Nantucket Tide Gage based on NOAA 2017

Year	NOAA2017 VLM	NOAA2017 Low	NOAA2017 Int-Low	NOAA2017 Intermediate	NOAA2017 Int-High	NOAA2017 High	NOAA2017 Extreme
2000	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2010	0.05	0.16	0.20	0.26	0.36	0.43	0.46
2020	0.10	0.36	0.43	0.59	0.79	0.92	0.95
2030	0.14	0.52	0.62	0.92	1.21	1.48	1.64
2040	0.19	0.72	0.85	1.28	1.77	2.26	2.49
2050	0.24	0.89	1.05	1.71	2.36	3.12	3.54
2060	0.29	1.08	1.31	2.17	3.05	4.13	4.82
2070	0.33	1.21	1.51	2.66	3.81	5.15	6.17
2080	0.38	1.38	1.71	3.22	4.66	6.36	7.71
2090	0.43	1.48	1.87	3.77	5.58	7.74	9.51
2100	0.48	1.57	2.03	4.33	6.56	9.25	11.42

Table 3: Predicted Relative Sea Level Rise Projections at NOAA Nantucket Tide Gage based on NOAA 2017

GMSL Rise Scenario	RCP 2.6	RCP 4.5	RCP 8.5
Low (0.3 m)	94%	98%	100%
Intermediate-Low (0.5 m)	49%	73%	96%
Intermediate (1.0 m)	2%	3%	17%
Intermediate-High (1.5 m)	0.4%	0.5%	1.3%
High (2.0 m)	0.1%	0.1%	0.3%
Extreme (2.5 m)	0.05%	0.05%	0.1%

Table 4: Probability of Exceeding Global Mean Sea Levels in 2100 for Several Representative Concentration Pathways (RCP) Scenarios relative to NOAA 2017 Global SLR Projections

Effect of Sea Level Rise on Extreme Water Levels

The relative sea level rise values can be linearly-superimposed to the predicted current tides and flood-frequency curves. **Table 5** indicates predicted sea level rise at Nantucket in the year 2070 relative to current (year 2020). **Table 6** presents predicted water levels for different Recurrence Intervals at Nantucket assuming NOAA 2017 Intermediate SLR Projection.

	Low	Int-Low	Int	Int-High	High	Extreme
2020	-	-	-	-	-	-
2030	0.16	0.26	0.56	0.85	1.12	1.28
2050	0.53	0.69	1.35	2.0	2.76	3.18
2070	0.85	1.15	2.30	3.45	4.79	5.81

Table 5: Predicted Sea Level Rise (in feet) at Nantucket for Six NOAA 2017 Projections

Data Source	Mean Stillwater Elevation (SWEL)					
	1 yr	**10 yr**	**20 yr**	**50 yr**	**100 yr**	**500 yr**
USACE NACCS 7380						
Year 2020	3.3	4.8	5.2	5.6	5.8	6.9
Year 2030	3.9	5.4	5.8	6.2	6.4	7.5
Year 2050	4.7	6.2	6.6	7.0	7.2	8.3
Year 2070	5.6	7.1	7.5	7.9	8.1	9.2

Table 6: Predicted Water Levels for different Recurrence Intervals at Nantucket assuming NOAA 2017 Intermediate SLR Projection

Synthetic Hydrographs

Synthetic hydrographs were developed to estimate representative storm durations. Hydrographs were developed for both: 1) tropical cyclones; and 2) extratropical nor'easters. The peak flood levels were fixed to the NACCS flood-frequency data for multiple recurrence intervals. The extratropical hydrographs utilized Storm Jun (January 26, 2015) as the base storm event. The tropical cyclones hydrographs utilized FHWA HEC 25 methods.

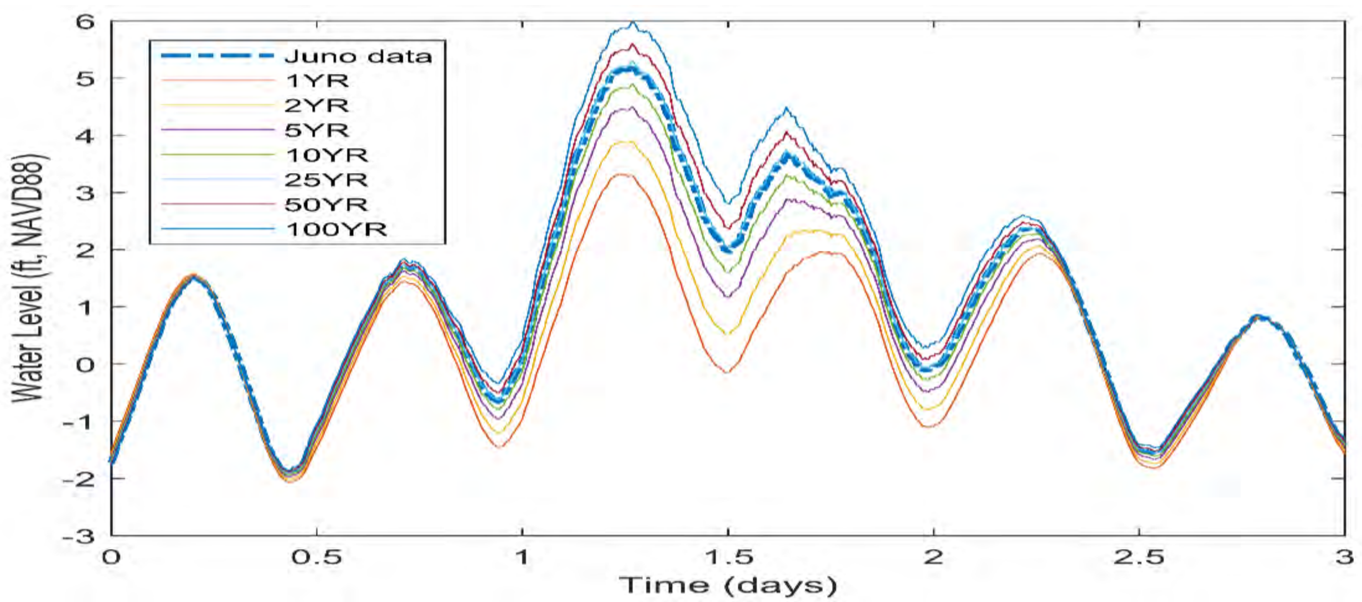


Figure 14: Synthetic hydrographs for nor'easters for NACCS estimates of flood water levels of 1YR, 2YR, 5YR, 10YR, 25YR, 50YR and 100YR return periods. The synthetic hydrographs are scaled based on observed water level data during Nor'easter Juno after 00:00 1/26/2015 EST at NOAA Nantucket tide gage

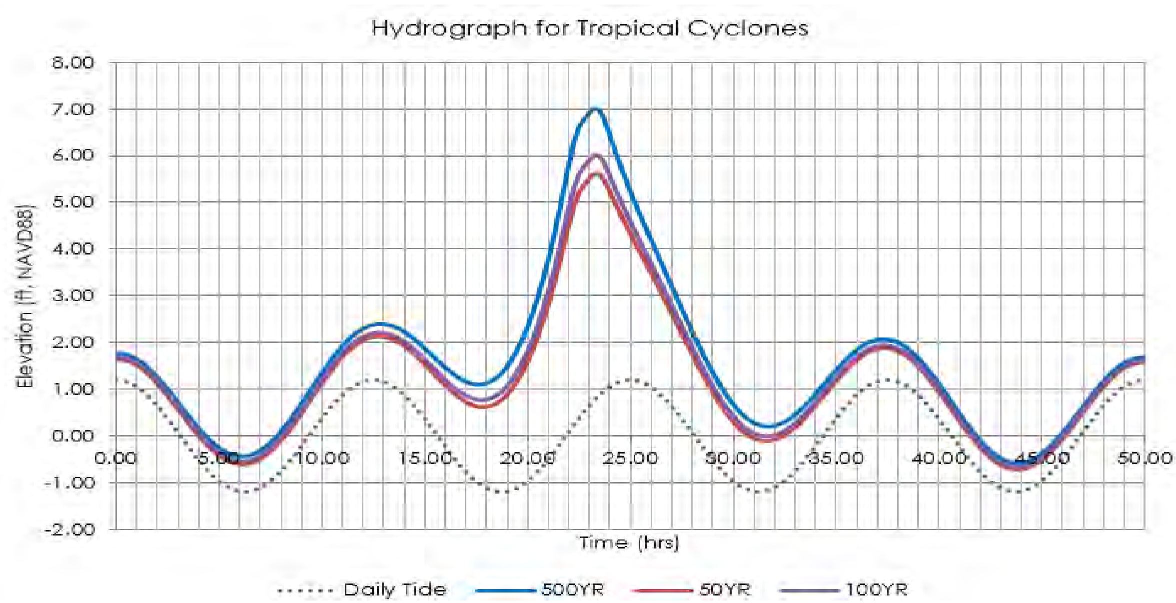


Figure 15: Synthetic hydrographs for Tropical Cyclones for NACCS estimates of flood water levels of 50YR, 100YR and 500YR return periods.

ATTACHMENT 6
Wave Model Results

Wave Modeling

GZA performed a numerical wave analysis using the SWAN (Simulating WAves Nearshore) model to evaluate waves generated by wind and deep water waves propagating toward the site (from the USACE Wave Information Studies [WIS] stations) for a range of different probabilities including the 1-year, 2-year, 5-year, 10-year, 25-year, 50-year, 100-year. SWAN is a third-generation wave model developed by the Delft University of Technology. SWAN calculates random, short-crested wind-generated waves in coastal regions and inland waters.

GZA performed a total of 28 wave simulations representing a range of different recurrence interval wind speeds and water levels. The simulated wave heights presented here represent significant wave heights, H_s and breaking wave heights, H_b (where depth limited wave conditions exist). Model simulation results were extracted at select, representative locations – see **Figure 7**.

Model Mesh Development

An unstructured model grid, consisting of 222,360 elements, was developed, extending approximately 20 miles offshore of Nantucket to the location of WIS wave buoy 63069. The model resolution ranged from 10 feet in vicinity of the Town Pier and the jetties to 3,000 feet at the open boundary. Model input, including stillwater elevation, boundary waves and model domain wind vectors, were simulated as a stationary-state condition.

The wave screen at the Town Pier and the walls of the adjacent boat basin were modeled in SWAN as obstacle barriers (of infinite height) that can reflect incident waves which influence the wave climate in vicinity of Town Pier. Both observation of waves at the site and model simulation indicate interaction between incident wave and reflected waves in front of the Town Pier wave screen.

Model DEM (Lidar)

The following data sources for bathymetry and topography were used to create the SWAN model grid Digital Elevation Model (DEM):

- 2016 NOAA NGS (National Geodetic Survey) Topobathy Lidar DEM: Martha's Vineyard and Nantucket Island, MA (the horizontal resolution is 3 feet).
- 2016 USACE Repairs to the East and West Jetties, Nantucket Harbor

The DEM dataset is presented in **Figures 1** through **Figure 5**. The SWAN model mesh is presented in **Figures 6** through **Figure 11**.

Model Simulations

The SWAN model simulations predict wave heights at the project site for the recurrence intervals: 1-year, 2-year, 5-year, 10-year, 25-year, 50-year, 100-year, and the model inputs for the SWAN wave sensitivity simulation scenarios are summarized in **Table 1** – **Table 3**, which include:

- Stillwater elevation based on USACE NACCS (North Atlantic Coast Comprehensive Study – see **Attachment 5**);
- Wind speed and direction were simulated for both the ASCE 7-10 and Nantucket Airport data (see **Attachment 4**);
- Deep water waves at the SWAN northern/eastern open boundary based on USACE WIS statistics at buoy 63069.

The SWAN output stations are shown in **Figures 7** through **13**. Simulated wave heights for the recurrence intervals of 1-year, 2-year, 5-year, 10-year, 25-year, 50-year, 100-year are summarized in **Tables 1** through **3**, and are presented in **Figure 4** – **Figure 64**.

Sensitivity Analysis

Sensitivity tests were first performed to evaluate: 1) the effects of varying wind direction on wave characteristics at the project site (results presented in **Table 1**, Runs 1 through 8); and 2) the effect of the harbor entrance jetties in attenuating ocean waves within the harbor (and at the Town Pier) (results presented in **Table 1**, Run 9). For Runs 1 through 7, the model inputs of water level, deepwater wave and wind speed are all for 100-year return period, while the wind direction varies from due east (90° in nautical custom) to due north (0° in nautical custom), which are described as Run 1 to Run 7 in **Table 1**. The sensitivity tests on wind direction indicates wind from north-northeast and northeast direction (i.e., Run 3 and Run 4) generates the highest wave height at the project site, and the simulated waves are presented in **Figures 14** through **48**. An additional simulation (Run 8) with wind direction between north-northeast and northeast (i.e., direction = 51°, Run 8) was performed to test the effects of a possible largest fetch to the project site, which creates similar waves as that by wind from north-northeast and northeast directions. Therefore, the northeast wind direction was selected as the representative conservative wind direction for wind generated waves at the project site.

To assess the effects of deepwater waves on wave condition at the project site (i.e., attenuating effects of the jetties at the harbor entrance), the model domain wind was turned off (for Run 9). The results indicate that ocean waves are nearly completely attenuated within the vicinity of the Town Pier and that waves that occur at the Town Pier are due principally to local wind fetch within Nantucket Harbor. For Run 9, the incident deepwater wave height is 33 feet at the model boundary which is 12 miles from the northern shoreline of Nantucket Island.

Design Model Simulations

Current Conditions: Design wave simulations were performed for prevailing wind conditions and for multiple recurrence interval conditions and for local winds speeds (based on both statistical analysis of Nantucket Airport (**Table 3**) and ASCE 7-10 (Table 2) - see **Attachment 4** for wind analysis details. Simulations using wind speeds based on ASCE 7-10 results are shown in **Table 2** and **Figures 54** through **58** and **Figures 65** through **79**, the associated peak wave periods and wave length are presented in **Table 3** and **Table 4**, respectively. Simulations using wind speeds based on GZA's analysis of Nantucket Airport are shown in **Table 5.**

The statistics of wave heights in the random sea follow the Rayleigh Probability Distribution, and the significant wave heights (H_s) shown in **Tables 1**, **2**, **5** indicate the average of the top 1/3 of the waves in the random sea. Based on the Rayleigh distribution, the statistics of wave heights was estimated and presented in **Table 6**: $H_{1/10}$ is the average of the top 10% of the waves (= 1.27 x H_s); $H_{1/100}$ is the average of the top 1% of the waves (= 1.67 x Hs); H_{max} is the maximum wave height (= 2.0 x H_s). The associated cumulative exceedance wave probabilities are: H_s is 13.5%; $H_{1/10}$ is 3.9%; and $H_{1/100}$ is 0.35%.

Sea Level Rise: Design simulations were also performed to evaluate the effect of sea level rise on wave height at the Town Pier. A sea level rise projection of 2 feet, based on NOAA 2017 Intermediate projection - see **Attachment 5** for details, was added for Runs #10A and #13A (**Table 2**). Wave heights at the project site increased by approximately 0.2 – 0.4 foot.

Barrier Beach Breach: Barrier beach overtopping is expected to occur during low probability extreme flood event. A barrier beach breach is unlikely considering the beach width and elevation. Regardless, a simulation was performed to evaluate a hypothetical 800-foot wide breach to a depth of Mean Low Water (Elevation -1.84 feet, NAVD88) at the northeast barrier beach directly across from the Town Pier (Run 13B; see **Figure 67** and **68**). The simulated wave heights (see **Figure 69** through **74**) at the Town Pier are the same as those without the breach (Run #13).

No Town Pier Wave Fence: A simulation was performed of the ASCE 7-10 wind speed, 100-year flood without the existing wave fence to evaluate: 1) the added value (sheltering effect) of the existing Town Pier wave fence; and 2) provide a base for comparison of additional improvements/modifications under consideration. See **Figure 75 Run 13D**.

Considered Improvements/Modifications to Town Pier Wave Fence and Nantucket Boat Basin Wave Fence

- **Extension of Town Pier Wave Fence**: The effect of extending the existing wave fence was simulated (see **Figure 80;** Run 13C). Structure improvements/modifications under consideration including extension of the existing Town Pier wave fence approximately 45 to the north and about 60 feet to the south. The wave heights in **Table 2** and **Figure 81** indicate the effects of extending the wave screen (up to 100 feet on the north end).
- **Extension of Town Pier Wave Fence**: The effect of extending the existing wave fence was simulated (see **Figure 82;** Run 13E). Structure improvements/modifications under consideration including extension of the existing Town Pier wave fence approximately 100 feet to the north. The wave heights in **Table 2** and **Figure 83** indicate the effects of extending the wave screen (up to 100 feet on the north end).
- **Extension of Nantucket Wave Fence**: The effect of extending the existing Nantucket Boat Basin wave fence was simulated (see **Figure 76;** Run 13F). Structure improvements/modifications under consideration including extension of the existing Town Pier wave fence. The wave heights in **Table 2** and **Figures 84** and **85** indicate the effects of extending the wave screen (up to 100 feet on the north end).
- **Extension of Nantucket Wave Fence and Town Pier Wave Fence**: The effect of extending the existing Nantucket Boat Basin wave fence and an approximately 100-foot extension of the north portion of the wave fence was simulated (see **Figure 76;** Run 13G). Structure improvements/modifications under consideration including

extension of the existing Town Pier wave fence approximately 100 feet to the north. The wave heights in **Table 2** and **Figures 86** and **87** indicate the effects of extending the wave screen (up to 100 feet on the north end).

Model Limitations

The presence of the Town Pier and adjacent boat basin wave screens affect the wave characteristics due to wave refraction and reflection. To model these effects, a high resolution model mesh and SWAN model "obstacle" features were utilized. The "obstacle" feature was selected to represent the wave screen in SWAN because it is the only model option that can create wave reflection. The SWAN model obstacle feature has two relevant limitations: 1) reflects 100% of the wave energy; and 2) has a theoretically infinite height (vertical elevation). Due to these limitations: 1) the reflected wave height in front of the wave screen (e.g., output point 1) may be overestimated by the infinite high obstacle that reflected 100% of the wave energy; 2) the actual wave crest elevation will exceed the top of the actual wave screen, resulting in wave overtopping and dissipation of wave energy. Regardless, the simulated wave heights behind the wave screen, to the shoreline, are expected to be accurate.

Table 1: SWAN Model Input and Output of Significant Wave Height at Output Points based on GZA Wind Analysis for 100YR Recurrence Interval

Run ID	SWAN Model Input					SWAN Model Output of Significant Wave Height (ft) at Output Points														
	Water Level[4] (ft, NAVD88)	Wave at Open Boundary		Wind																
		Sig. Wave Height[3] (ft)	Direction[1] (°)	Speed[2] (mph)	Direction[1] (°)	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
#1	6	33	90	70	90	3.9	2.2	2.5	2.5	2.2	2.8	3.3	2.9	2.8	2.6	11.6	4.9	3.3	2.2	6.3
#2	6	33	75	70	75	4.2	2.1	2.6	2.6	2.3	2.9	3.3	2.9	3.0	2.6	11.7	6.3	4.4	2.7	6.7
#3	6	33	60	70	60	4.4	2.2	2.6	2.7	2.3	3.0	3.4	2.8	3.3	2.6	11.6	7.3	5.0	3.7	7.2
#4	6	33	45	70	45	4.4	2.2	2.5	2.6	2.2	3.0	3.6	2.7	3.4	2.6	11.5	7.8	5.3	5.2	7.8
#5	6	33	30	70	30	4.3	2.2	2.4	2.5	2.2	2.9	3.5	2.5	3.5	2.5	11.4	8.2	5.4	7.1	8.4
#6	6	33	15	70	15	4.0	2.1	2.5	2.2	2.6	2.7	3.1	2.4	3.4	2.5	11.2	8.4	5.5	9.1	8.8
#7	6	33	0	70	0	3.4	1.8	2.5	2.0	2.5	2.3	2.8	2.1	3.3	2.7	10.8	8.5	5.6	10.8	9.1
#8	6	33	51	70	51	4.4	2.2	2.5	2.7	2.3	3.0	3.6	2.8	3.4	2.6	11.6	7.6	5.2	4.6	7.5
#9	6	33	51	N/A	N/A	0.1	0.0	0.0	0.0	0.0	0.1	0.1	0.2	0.1	0.0	13.0	7.7	5.3	2.4	9.0

Notes:

1. Wind and wave direction in nautical custom. 0° indicates direction from due north; 90° indicates direction from due east;
2. Wind speed is in 1-min averaging duration, and is based on GZA frequency analysis using observed wind data at Nantucket Memorial Airport;
3. Significant wave height at open boundary is based on USACE extreme analysis at WIS wave buoy 63069;
4. Water level is based on average of NACCS estimate of 5.9 ft, NAVD88 and FEMA estimate of 6.1 ft, NAVD88 for 100YR return period.

Table 2: SWAN Model Input and Output of Significant Wave Height at Output Points based on ASCE Wind Analysis for Return Periods of 10YR, 25YR, 50YR and 100YR

Run ID	SWAN Model Input					SWAN Model Output of Significant Wave Height (ft) at Output Points														
	Water Level[4] (ft, NAVD88)	Wave at Open Boundary		Wind																
		Sig. Wave Height[3] (ft)	Direction[1] (°)	Speed[2] (mph)	Direction[1] (°)	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
#10 (10YR)	4.9	26	45	65	45	4.1	2.0	2.3	2.4	2.1	2.7	3.3	2.5	3.1	2.4	11.1	7.2	4.8	4.9	7.1
#10A (10YR)[5]	6.9	26	45	65	45	4.3	2.2	2.4	2.5	2.2	2.9	3.5	2.7	3.3	2.4	11.8	8.0	5.6	5.1	7.9
#11 (25YR)	5.3	28	45	81	45	4.7	2.4	2.8	2.8	2.5	3.2	3.9	2.9	3.7	2.9	11.4	7.6	5.0	5.6	7.5
#12 (50YR)	5.6	31	45	89	45	5.1	2.6	3.0	3.0	2.7	3.4	4.2	3.1	4.0	3.1	11.5	7.8	5.2	5.9	7.7
#13 (100YR)	6.0	33	45	98	45	5.4	2.7	3.2	3.2	2.8	3.7	4.5	3.2	4.3	3.3	11.7	8.1	5.4	6.1	7.9
#13A (100YR)[5]	8.0	33	45	98	45	5.7	2.9	3.4	3.4	3.0	3.9	4.8	3.6	4.6	3.5	12.5	8.9	6.2	6.4	8.7
#13B (100YR)[6]	6.0	33	45	98	45	5.4	2.7	3.2	3.2	2.8	3.7	4.5	3.2	4.2	4.0	11.7	8.1	5.4	6.1	7.9
#13C (100YR)[7]	6.0	33	45	98	45	5.3	2.0	2.9	2.7	2.5	3.7	4.5	3.2	4.3	3.3	11.7	8.1	5.4	6.1	7.9
#13D (100YR)[8]	6.0	33	45	98	45	4.4	3.7	3.6	4.0	3.8	3.7	4.5	3.2	4.3	3.3	11.7	8.1	5.4	6.1	7.9
#13E (100YR)[9]	6.0	33	45	98	45	5.5	1.1	2.3	2.7	2.8	3.7	4.5	3.2	4.3	3.3	11.7	8.1	5.4	6.1	7.9
#13F (100YR)[10]	6.0	33	45	98	45	5.1	2.4	2.9	3.1	2.7	3.7	4.5	3.2	4.3	3.3	11.7	8.1	5.4	6.1	7.9
#13G (100YR)[11]	6.0	33	45	98	45	5.2	0.9	2.4	3.1	2.8	3.7	4.5	3.2	4.3	3.3	11.7	8.1	5.4	6.1	7.9

Table 2 Notes:

1. Wind and wave direction in nautical custom. 0º indicates direction from due north; 90º indicates direction from due east;
2. Wind speed is in 1-min averaging duration, and is based on ASCE 7-10 wind;
3. Significant wave height at open boundary is based on USACE extreme analysis at WIS wave buoy 63069;
4. Water level is based on NACCS estimate for 10YR, 25YR and 50YR return periods; water level for 100YR is based on average of NACCS estimate of 5.9 ft, NAVD88 and FEMA estimate of 6.1 ft, NAVD88.
5. Includes sea level rise of 2 feet in 2060.
6. Includes hypothetical breach in model mesh.
7. Includes hypothetical extension of wave screen.
8. Wave fence is removed from model.
9. Includes hypothetical extension of wave screen.
10. Structure improvements/modifications under consideration including extension of Nantucket Boat Basin with No Change to Town Pier.
11. Structure improvements/modifications under consideration including extension of Nantucket Boat Basin with about north 100 foot extension to Town Pier.

Table 3: SWAN Model Input and Output of Peak Wave Period at Output Points based on ASCE Wind Analysis for Return Periods of 10YR, 25YR, 50YR and 100YR

Run ID	SWAN Model Input					SWAN Model Output of Peak Wave Period (s) at Output Points														
	Water Level[4] (ft, NAVD88)	Wave at Open Boundary		Wind																
		Sig. Wave Height[3] (ft)	Direction[1] (°)	Speed[2] (mph)	Direction[1] (°)	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
#10 (10YR)	4.9	26	45	65	45	3.3	3.2	3.3	3.3	3.3	3.0	3.2	2.9	3.3	2.6	8.4	8.4	8.3	4.3	8.3
#10A (10YR)[5]	6.9	26	45	65	45	3.5	3.4	3.4	3.5	3.4	3.2	3.4	3.3	3.5	2.6	8.4	8.4	8.3	8.0	8.3
#11 (25YR)	5.3	28	45	81	45	3.5	3.4	3.5	3.5	3.5	3.2	3.5	3.1	3.5	2.7	8.4	8.4	10.0	4.5	8.3
#12 (50YR)	5.6	31	45	89	45	3.6	3.5	3.6	3.6	3.6	3.3	3.5	3.1	3.6	2.8	8.4	8.4	10.1	4.6	8.3
#13 (100YR)	6.0	33	45	98	45	3.7	3.6	3.6	3.7	3.6	3.3	3.7	3.2	3.8	2.9	8.4	10.0	10.1	4.7	8.3
#13A (100YR)[5]	8.0	33	45	98	45	3.9	3.8	3.8	3.9	3.8	3.5	3.8	3.5	3.9	3.0	8.4	10.0	10.0	4.8	8.3
#13B (100YR)[6]	6.0	33	45	98	45	3.7	3.6	3.6	3.7	3.6	3.3	3.7	3.2	3.7	3.0	8.4	10.0	10.1	4.7	8.3
#13C (100YR)[7]	6.0	33	45	98	45	3.7	3.5	3.6	3.7	3.6	3.3	3.7	3.2	3.8	2.9	8.4	10.0	10.1	4.7	8.3
#13D (100YR)[8]	6.0	33	45	98	45	3.7	3.6	3.7	3.7	3.7	3.3	3.7	3.2	3.8	2.9	8.4	10.0	10.1	4.7	8.3
#13E (100YR)[9]	6.0	33	45	98	45	3.7	4.1	3.6	3.7	3.8	3.3	3.7	3.2	3.8	2.9	8.4	10.0	10.1	4.7	8.3

Notes:

1. Wind and wave direction in nautical custom. 0° indicates direction from due north; 90° indicates direction from due east;
2. Wind speed is in 1-min averaging duration, and is based on ASCE 7-10 wind;
3. Significant wave height at open boundary is based on USACE extreme analysis at WIS wave buoy 63069;
4. Water level is based on NACCS estimate for 10YR, 25YR and 50YR return periods; water level for 100YR is based on average of NACCS estimate of 5.9 ft, NAVD88 and FEMA estimate of 6.1 ft, NAVD88.
5. Includes sea level rise of 2 feet in 2060.
6. Includes hypothetical breach in model mesh.
7. Includes hypothetical extension of wave screen.
8. Wave fence is removed from model.
9. Includes hypothetical extension of wave screen.

Table 4: SWAN Model Input and Output of Wave Length at Output Points based on ASCE Wind Analysis for Return Periods of 10YR, 25YR, 50YR and 100YR

Run ID	SWAN Model Input					SWAN Model Output of Wave Length (ft) at Output Points														
	Water Level[4] (ft, NAVD88)	Wave at Open Boundary		Wind																
		Sig. Wave Height[3] (ft)	Direction[1] (°)	Speed[2] (mph)	Direction[1] (°)	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
#10 (10YR)	4.9	26	45	65	45	29	23	22	23	16	20	25	19	24	18	185	139	93	42	135
#10A (10YR)[5]	6.9	26	45	65	45	32	25	24	25	17	21	27	20	26	18	193	147	98	44	145
#11 (25YR)	5.3	28	45	81	45	35	26	21	26	16	21	29	20	27	19	181	133	89	46	135
#12 (50YR)	5.6	31	45	89	45	37	28	22	28	18	22	31	20	28	20	180	130	88	47	137
#13 (100YR)	6.0	33	45	98	45	39	29	25	29	19	24	33	21	30	20	178	125	83	49	139
#13A (100YR)[5]	8.0	33	45	98	45	43	32	27	31	20	27	37	24	33	21	188	134	88	50	149
#13B (100YR)[6]	6.0	33	45	98	45	39	29	25	29	19	24	33	21	30	22	178	125	83	49	139
#13C (100YR)[7]	6.0	33	45	98	45	39	25	23	27	15	24	33	21	30	20	178	125	83	49	139
#13D (100YR)[8]	6.0	33	45	98	45	33	28	27	30	28	24	33	21	30	20	179	126	84	49	139
#13E (100YR)[9]	6.0	33	45	98	45	41	29	17	30	13	24	33	21	30	20	178	125	83	49	139

Notes:

1. Wind and wave direction in nautical custom. 0° indicates direction from due north; 90° indicates direction from due east;
2. Wind speed is in 1-min averaging duration, and is based on ASCE 7-10 wind;
3. Significant wave height at open boundary is based on USACE extreme analysis at WIS wave buoy 63069;
4. Water level is based on NACCS estimate for 10YR, 25YR and 50YR return periods; water level for 100YR is based on average of NACCS estimate of 5.9 ft, NAVD88 and FEMA estimate of 6.1 ft, NAVD88.
5. Includes sea level rise of 2 feet in 2060.
6. Includes hypothetical breach in model mesh.
7. Includes hypothetical extension of wave screen.
8. Wave fence is removed from model.
9. Includes hypothetical extension of wave screen.

Table 5; SWAN Model Input and Output of Significant Wave Height at Output Points based on GZA Wind Analysis for Return Periods of 1YR, 2YR, 5YR, 10YR, 25YR, 50YR and Prevailing Wind Speeds

Run ID	SWAN Model Input					SWAN Model Output of Significant Wave Height (ft) at Output Points														
	Water Level[4] (ft, NAVD88)	Wave at Open Boundary		Wind																
		Sig. Wave Height (ft)	Direction[1] (°)	Speed[2] (mph)	Direction[1] (°)	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
#14 (1YR)	3.3	18	45	35	45	2.3	1.1	1.2	1.3	1.1	1.5	1.8	1.4	1.8	1.7	9.8	5.8	4.0	3.4	6.0
#15 (2YR)	3.9	20	45	50	45	3.2	1.6	1.8	1.9	1.6	2.1	2.5	1.9	2.4	1.9	10.5	6.5	4.3	4.2	6.5
#16 (5YR)	4.5	23	45	57	45	3.6	1.8	2.0	2.2	1.8	2.4	2.9	2.2	2.8	2.1	10.8	6.9	4.6	4.6	6.9
#17 (10YR)	4.9	26	45	61	45	3.9	1.9	2.2	2.3	2.0	2.6	3.1	2.3	3.0	2.2	11.0	7.2	4.8	4.8	7.1
#18 (25YR)	5.3	28	45	65	45	4.1	2.1	2.3	2.4	2.1	2.7	3.3	2.5	3.2	2.4	11.2	7.4	5.0	5.0	7.3
#19 (50YR)	5.6	31	45	68	45	4.3	2.2	2.4	2.5	2.2	2.9	3.5	2.6	3.3	2.5	11.4	7.6	5.1	5.1	7.5
#20 (Prevail-ing)	1.2	NA	NA	17	45	1.4	0.7	0.7	0.8	0.7	1.1	1.2	0.6	0.7	0	1.6	0.9	0.8	0.5	1.6

Notes:

1. Wind and wave direction in nautical custom. 0° indicates direction from due north; 90° indicates direction from due east;
2. Wind speed is in 1-min averaging duration, and is based on GZA frequency analysis using observed wind data at Nantucket Memorial Airport;
3. Significant wave height at open boundary is based on USACE extreme analysis at WIS wave buoy 63069;
4. Water level is based on NACCS estimate.

Table 6: SWAN Model Input and Output of Wave Length at Output Points based on ASCE Wind Analysis for Return Periods of 10YR, 25YR, 50YR and 100YR

Return Period	Wave Heights[4]	Simulated Wave Heights using ASCE Wind[1] at Output Points[3]				Simulated Wave Heights using GZA Wind[2] at Output Points[3]			
		#2	#3	#4	#5	#2	#3	#4	#5
10YR	H_s	2.0	2.3	2.4	2.1	1.9	2.2	2.3	2.0
	$H_{1/10}$	2.5	2.9	3.0	2.7	2.4	2.8	2.9	2.5
	$H_{1/100}$	3.3	3.8	4.0	3.5	3.2	3.7	3.8	3.3
	H_{max}	4.0	4.6	4.8	4.2	3.8	4.4	4.6	4.0
50YR	H_s	2.6	3.0	3.0	2.7	2.2	2.4	2.5	2.2
	$H_{1/10}$	3.3	3.8	3.8	3.4	2.8	3.0	3.2	2.8
	$H_{1/100}$	4.3	5.0	5.0	4.5	3.7	4.0	4.2	3.7
	H_{max}	5.2	6.0	6.0	5.4	4.4	4.8	5.0	4.4
100YR	H_s	2.7	3.2	3.2	2.8	2.2	2.5	2.6	2.2
	$H_{1/10}$	3.4	4.1	4.1	3.6	2.8	3.2	3.3	2.8
	$H_{1/100}$	4.5	5.3	5.3	4.7	3.7	4.2	4.3	3.7
	H_{max}	5.4	6.4	6.4	5.6	4.4	5.0	5.2	4.4

Notes:

1. SWAN model input conditions are presented in Table 2;
2. SWAN model input conditions are presented in Table 5;
3. Output point locations are indicated in Figure 10;
4. H_s: significant wave height, results of significant wave heights in this table are consistent with Table 2 for ASCE wind, and consistent with Table 5 for GZA wind; $H_{1/10}$: average of the top 10% of the waves (= 1.27 x H_s); $H_{1/100}$: average of the top 1% of the waves (= 1.67 x H_s); H_{max}: maximum wave height (= 2.0 x H_s).

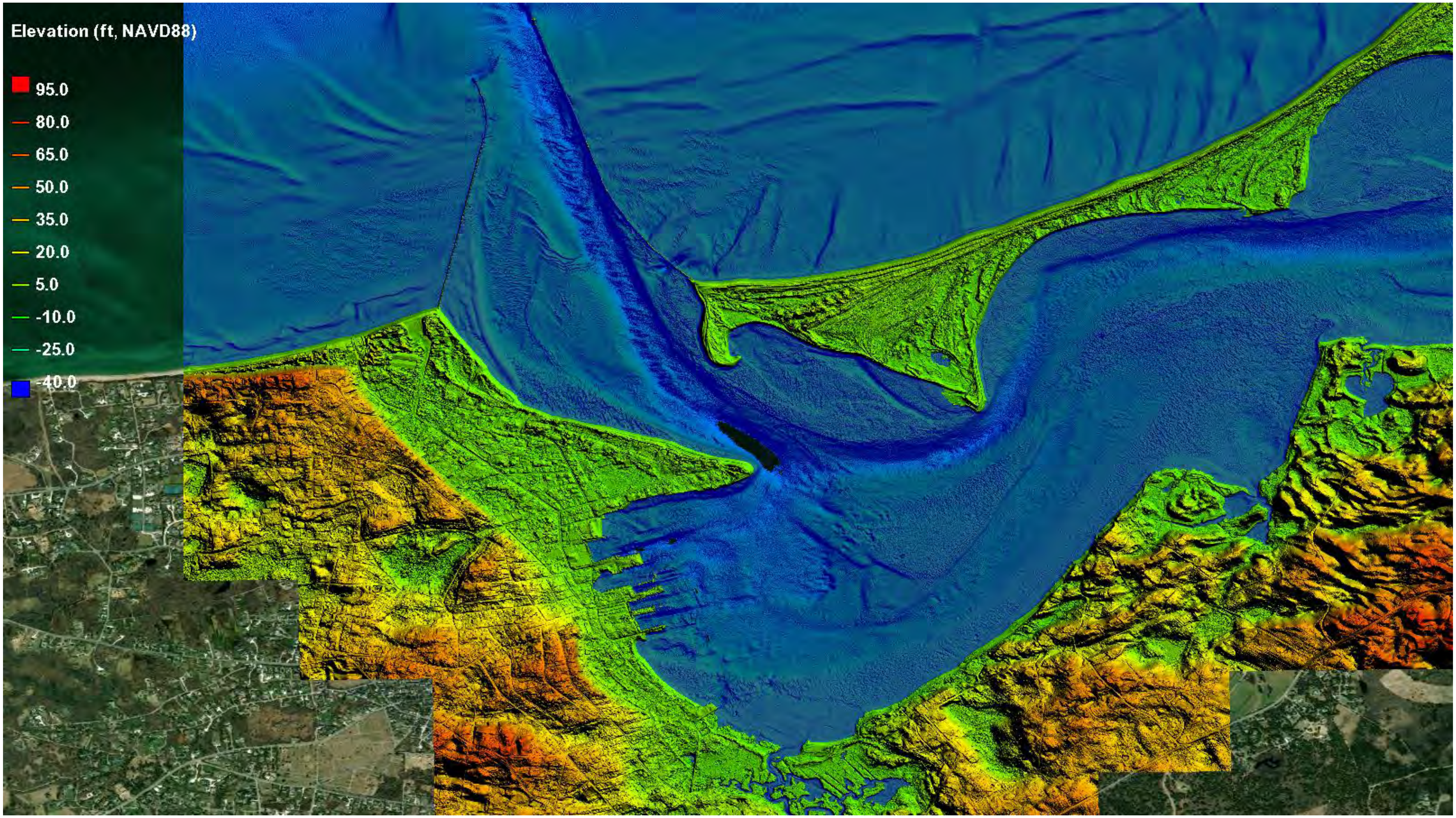


Figure 1: 2016 NOAA NGS (National Geodetic Survey) Topobathy Lidar DEM: Martha's Vineyard and Nantucket Island, MA.
metadata: https://inport.nmfs.noaa.gov/inport/item/51268

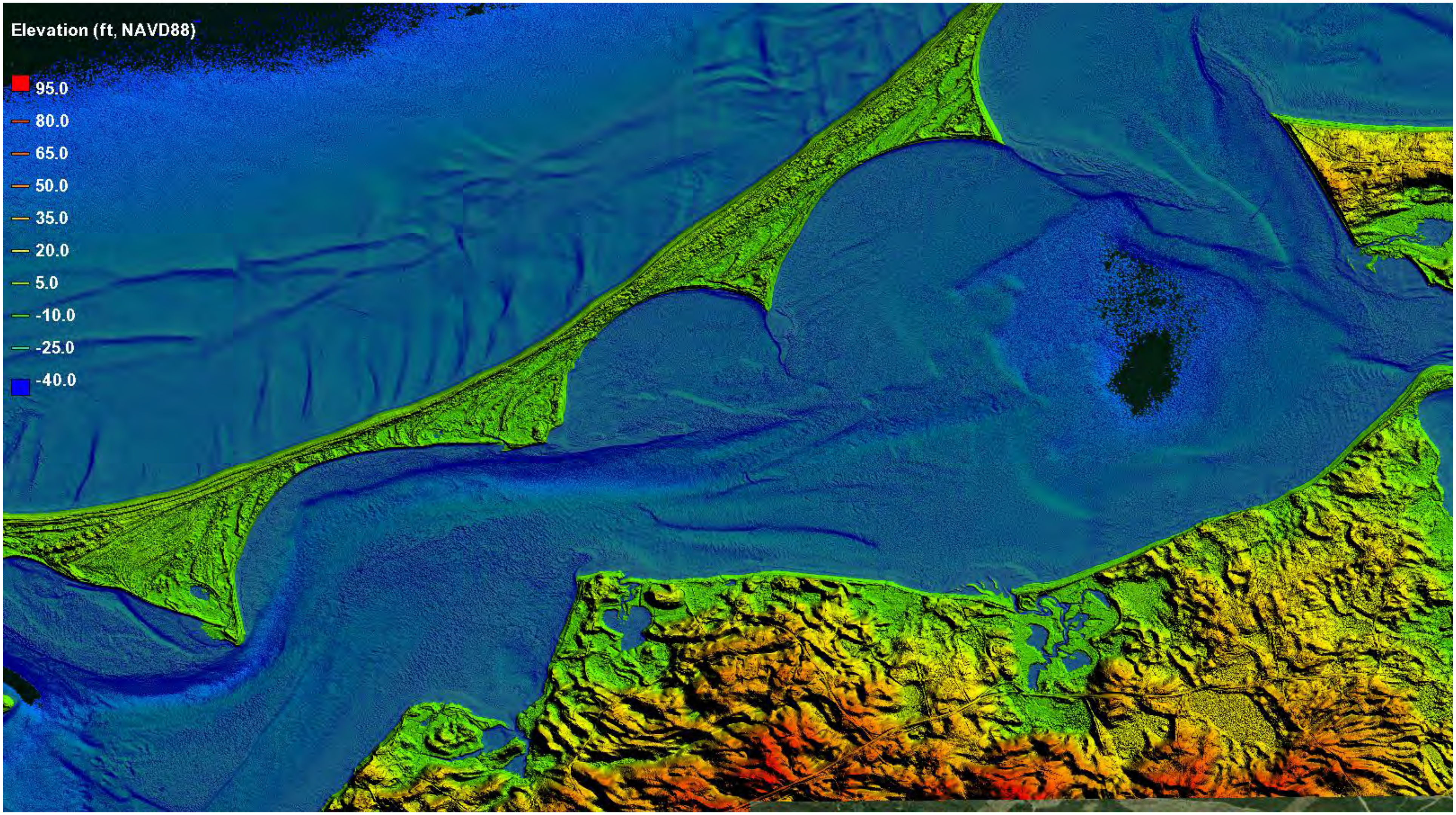


Figure 2: 2016 NOAA NGS (National Geodetic Survey) Topobathy Lidar DEM: Marthas Vineyard and Nantucket Island, MA.
metadata: https://inport.nmfs.noaa.gov/inport/item/51268

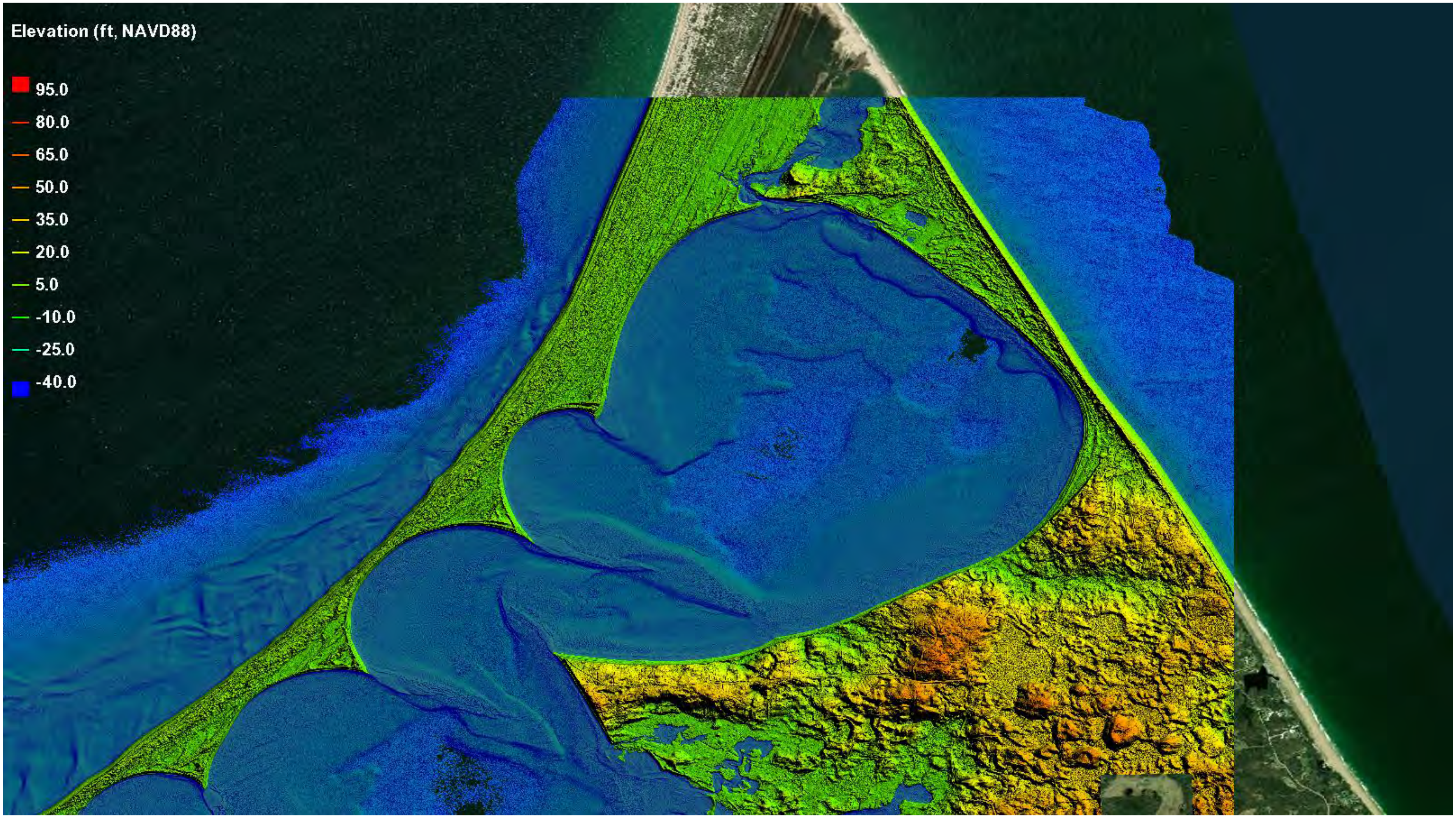


Figure 3: 2016 NOAA NGS (National Geodetic Survey) Topobathy Lidar DEM: Marthas Vineyard and Nantucket Island, MA.
metadata: https://inport.nmfs.noaa.gov/inport/item/51268

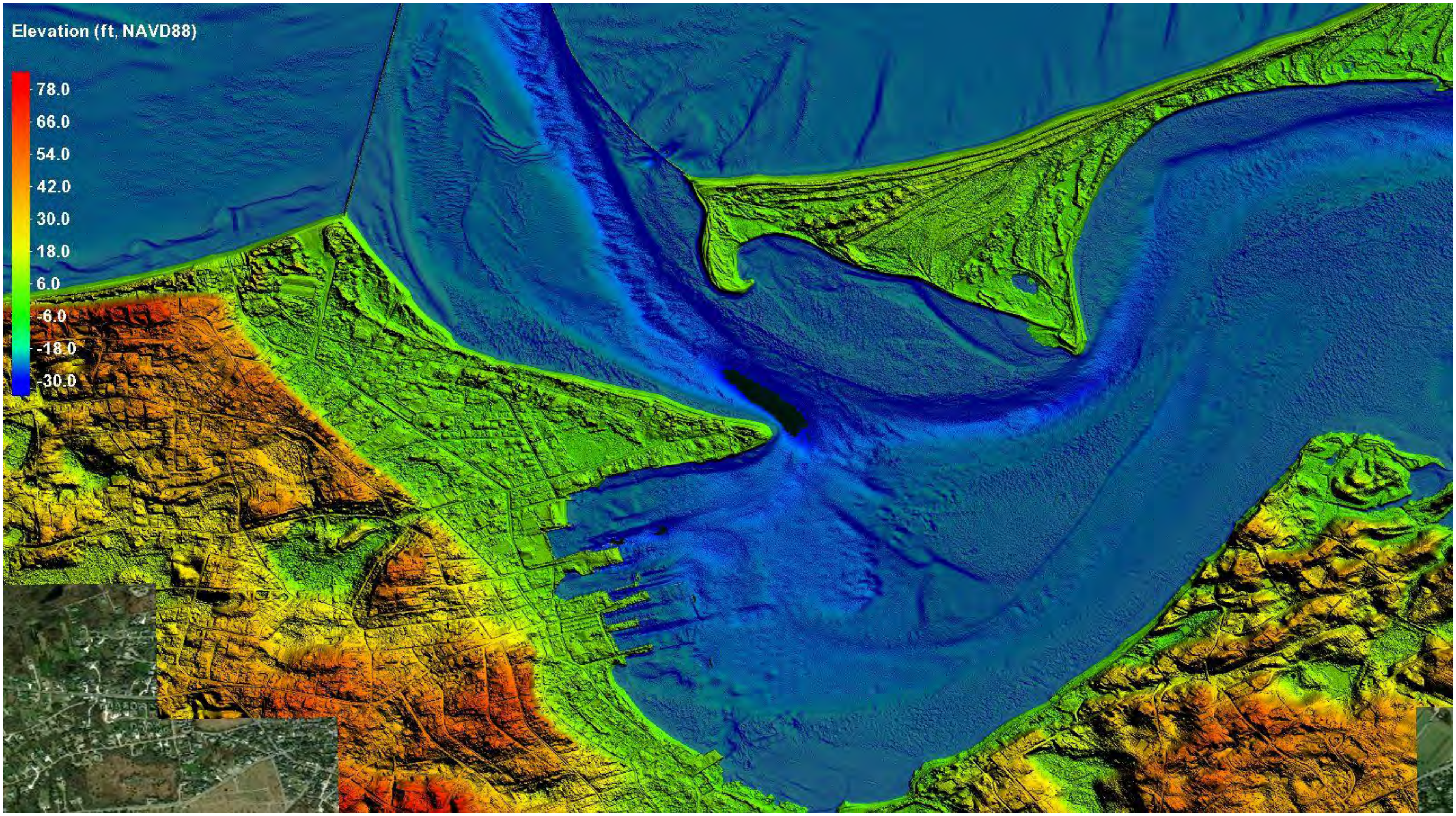


Figure 4: 2016 NOAA NGS (National Geodetic Survey) Topobathy Lidar DEM: Marthas Vineyard and Nantucket Island, MA.
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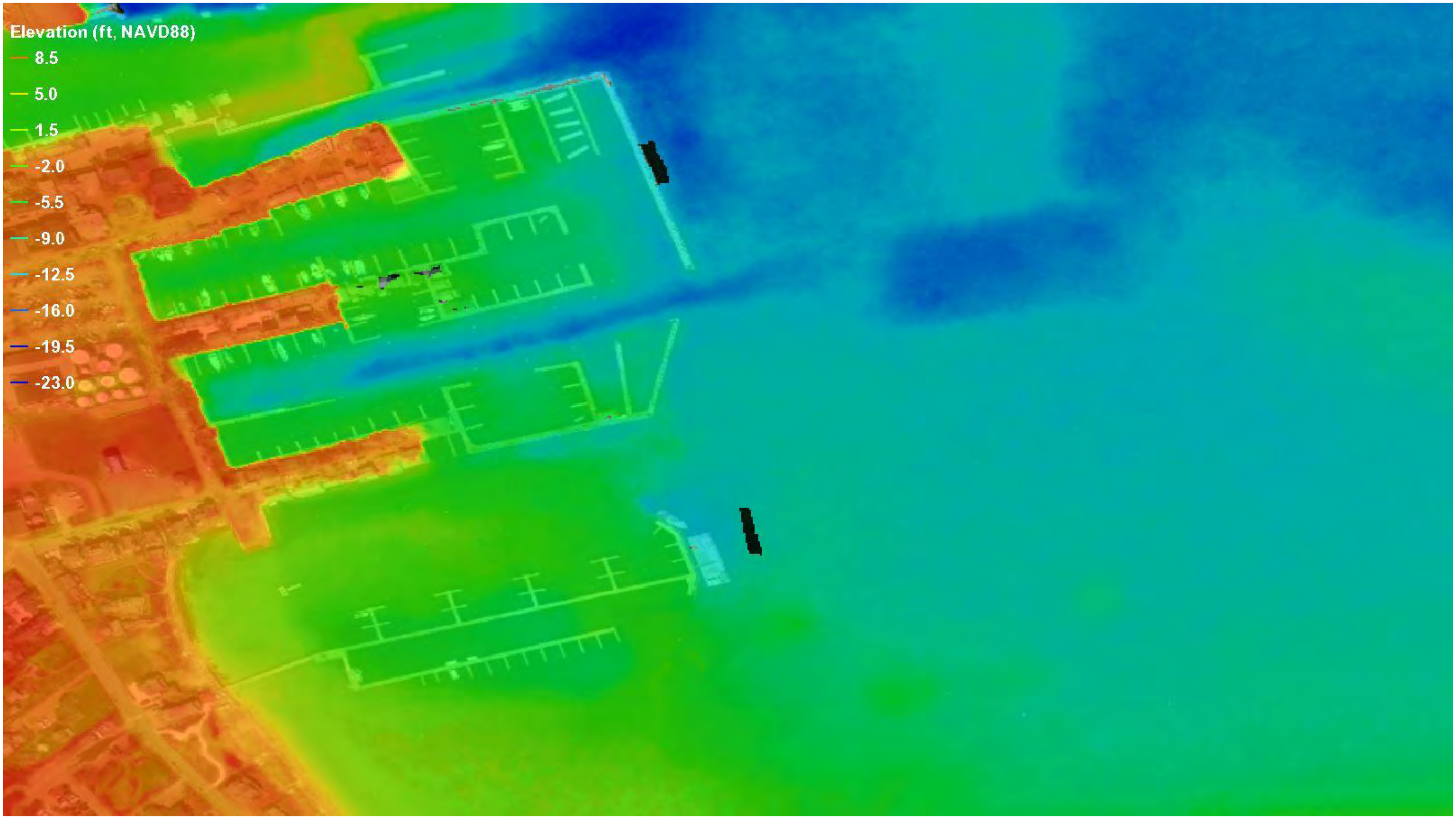

Figure 5: 2016 NOAA NGS (National Geodetic Survey) Topobathy Lidar DEM: Marthas Vineyard and Nantucket Island, MA.
metadata: https://inport.nmfs.noaa.gov/inport/item/51268

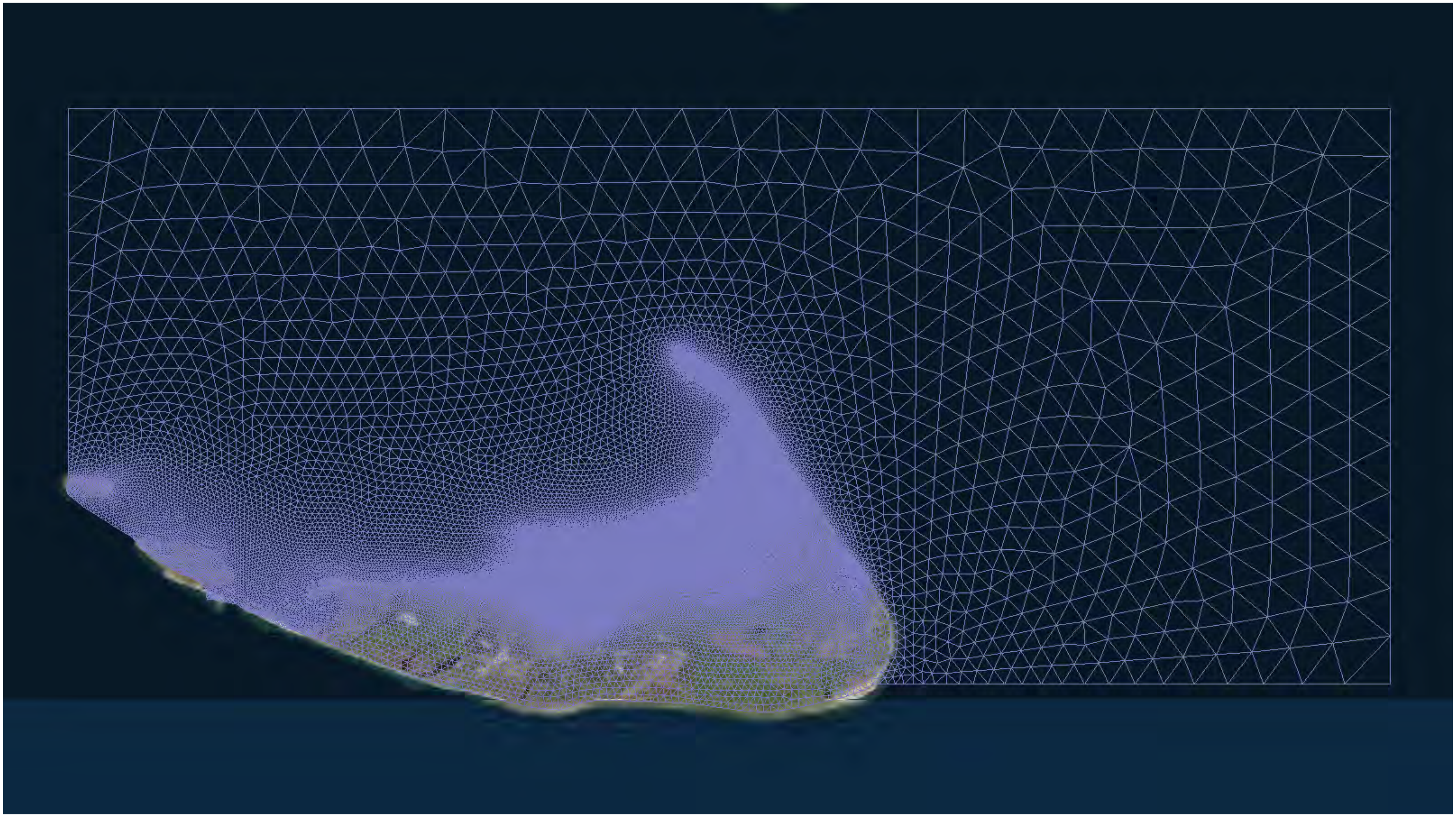

Figure 6: SWAN Model Mesh

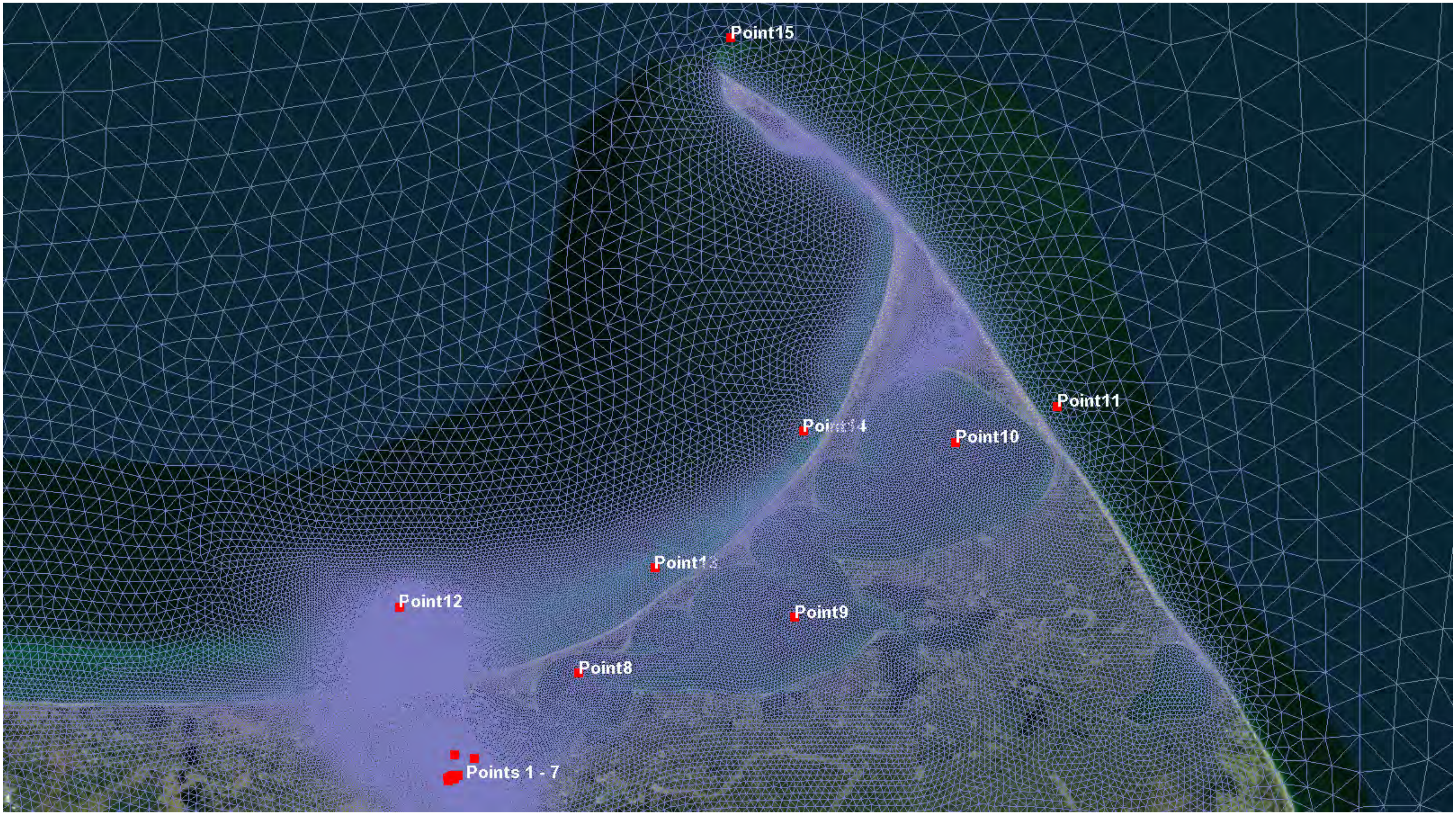

Figure 7: SWAN Model Mesh

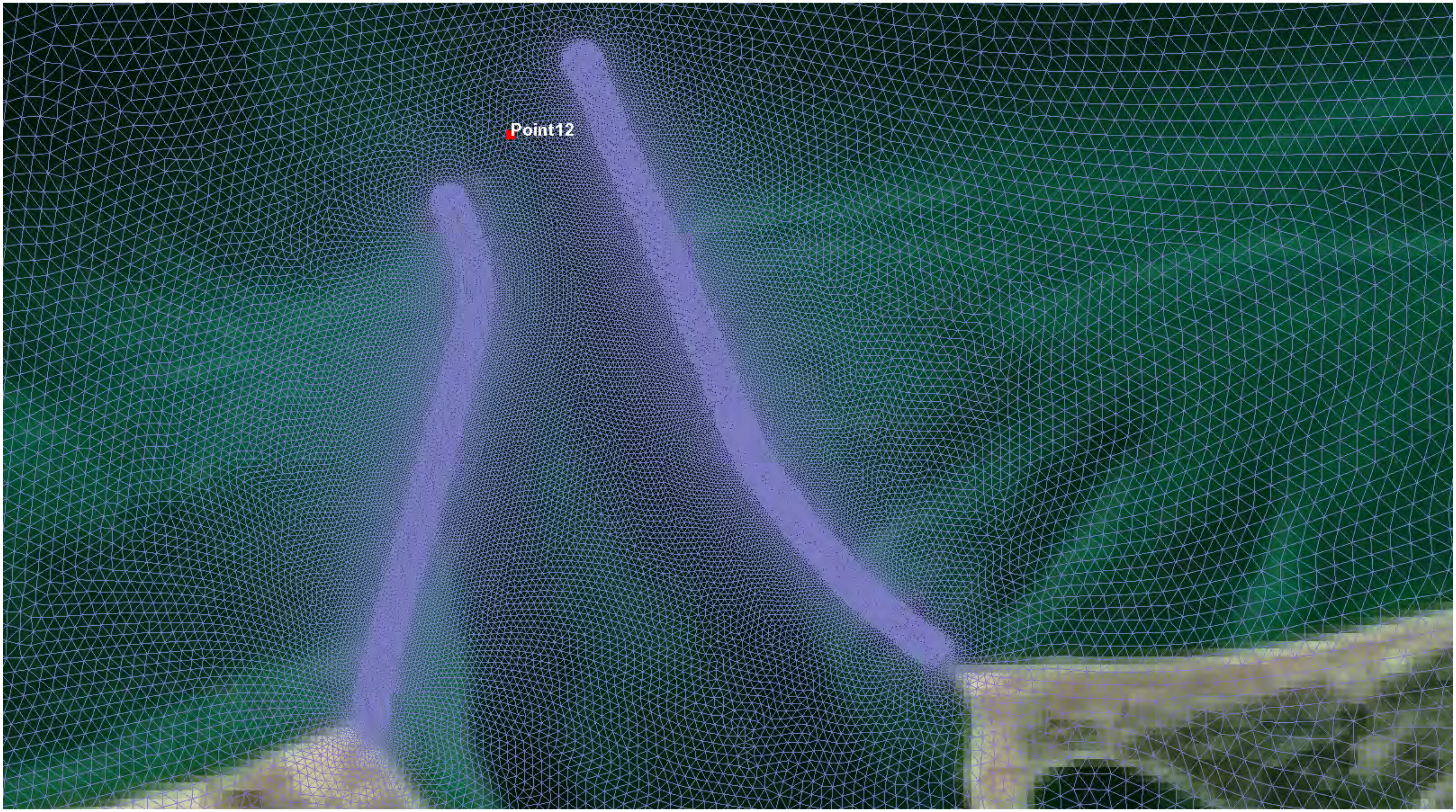

Figure 8: SWAN Model Mesh at Jetty and Output Point 12

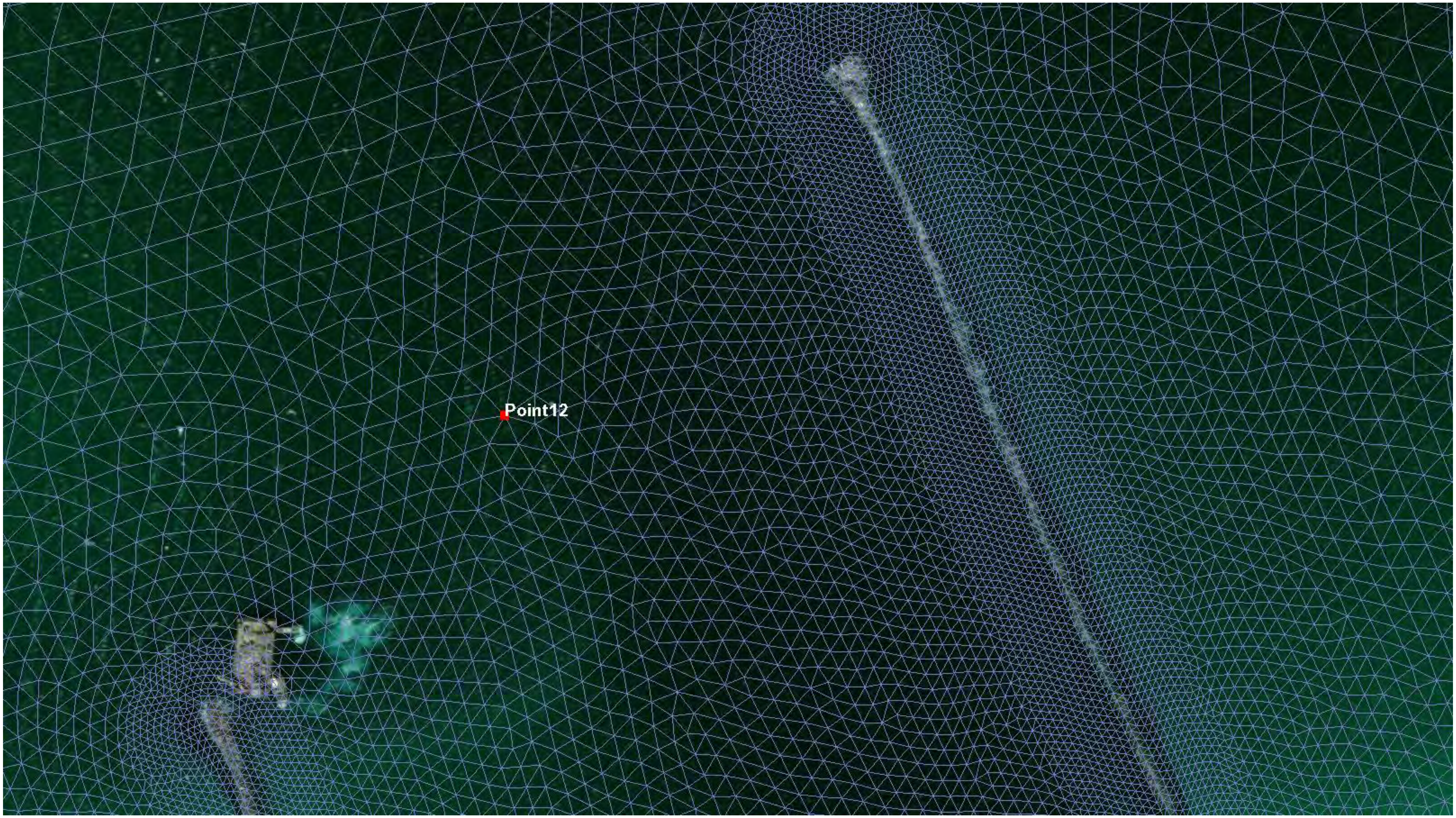

Figure 9: SWAN Model Mesh at Jetty with resolution in approximately 10 feet

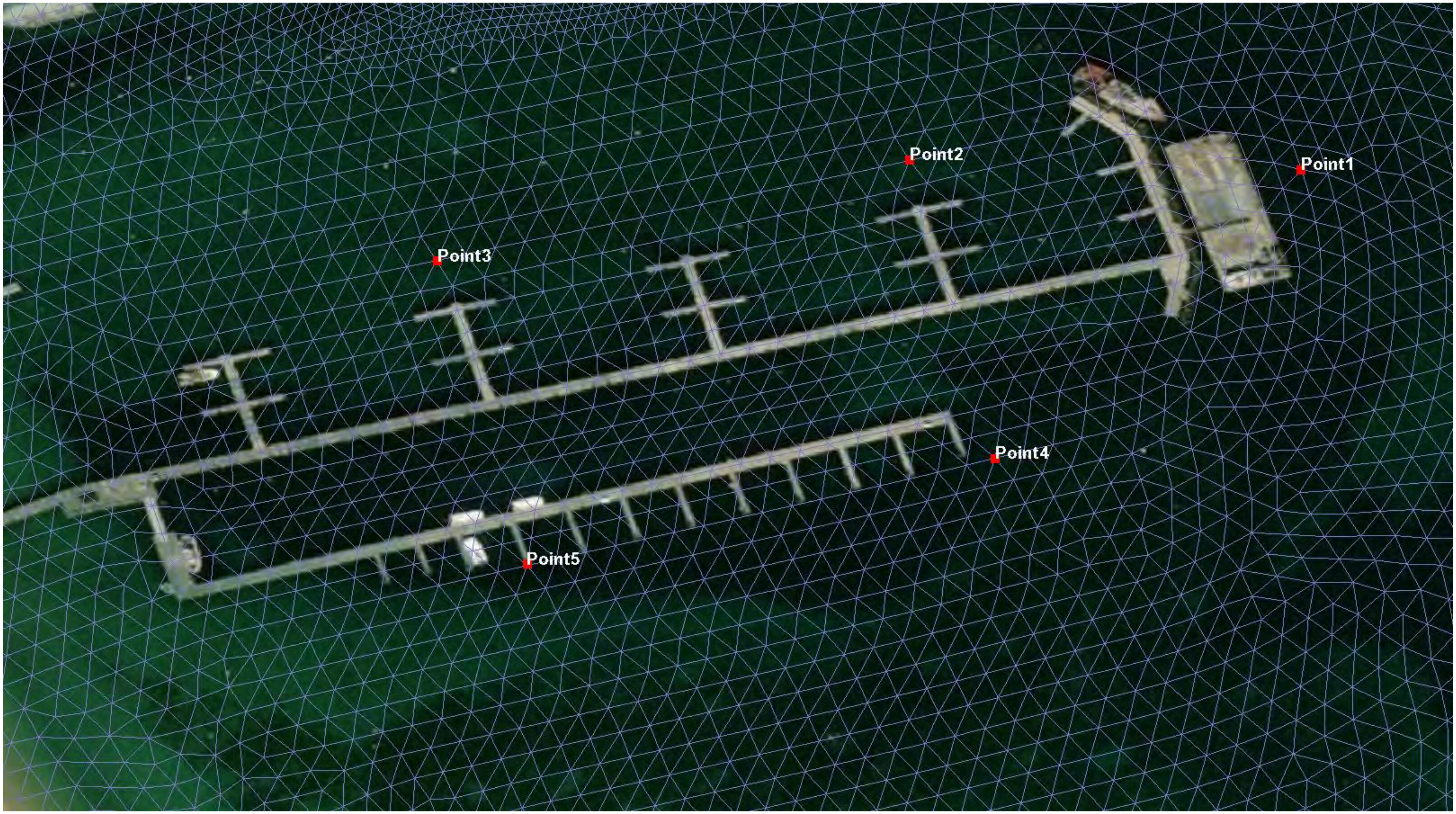

Figure 10: SWAN Model Mesh at the Town Pier and Model Output Points 1 – 5

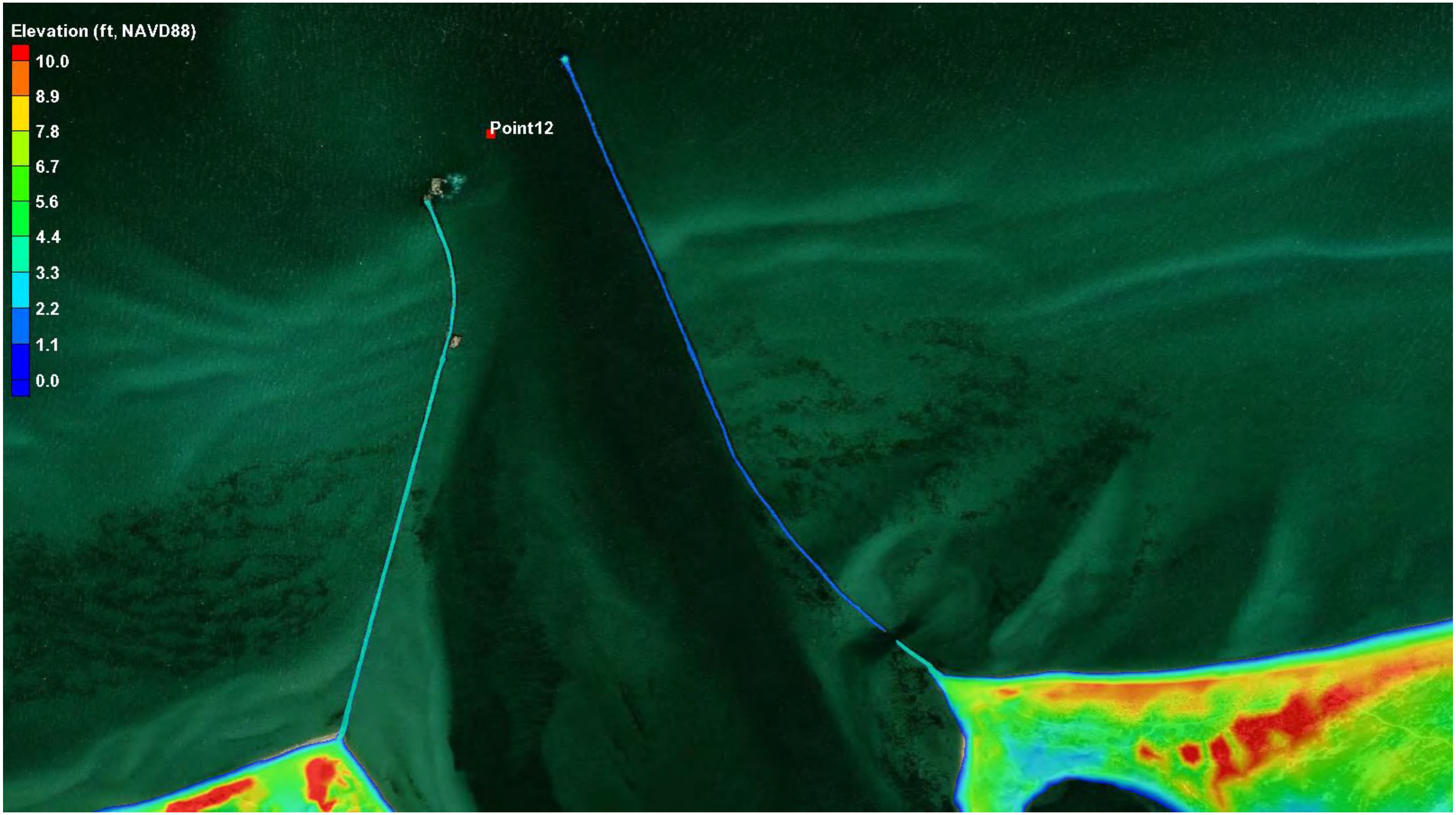

Figure 11: SWAN Model DEM at Jetty based on USACE (2015)

Figure 12: SWAN Model Output Points 1 – 7

Figure 13: SWAN Model Output Points 1 – 15

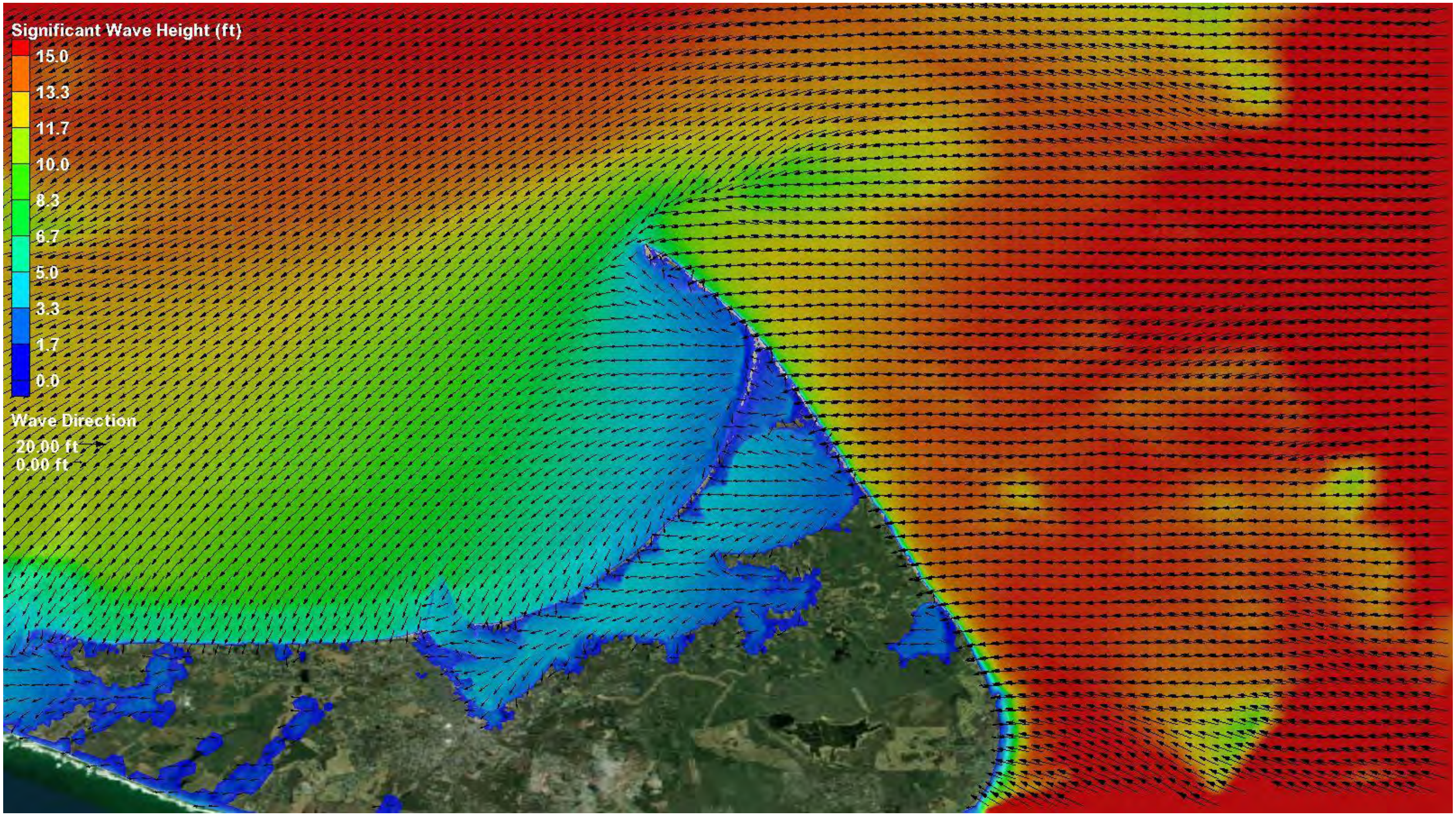

Figure 14: Significant Wave Height simulated by SWAN Wave Model for Run #1 – view 1

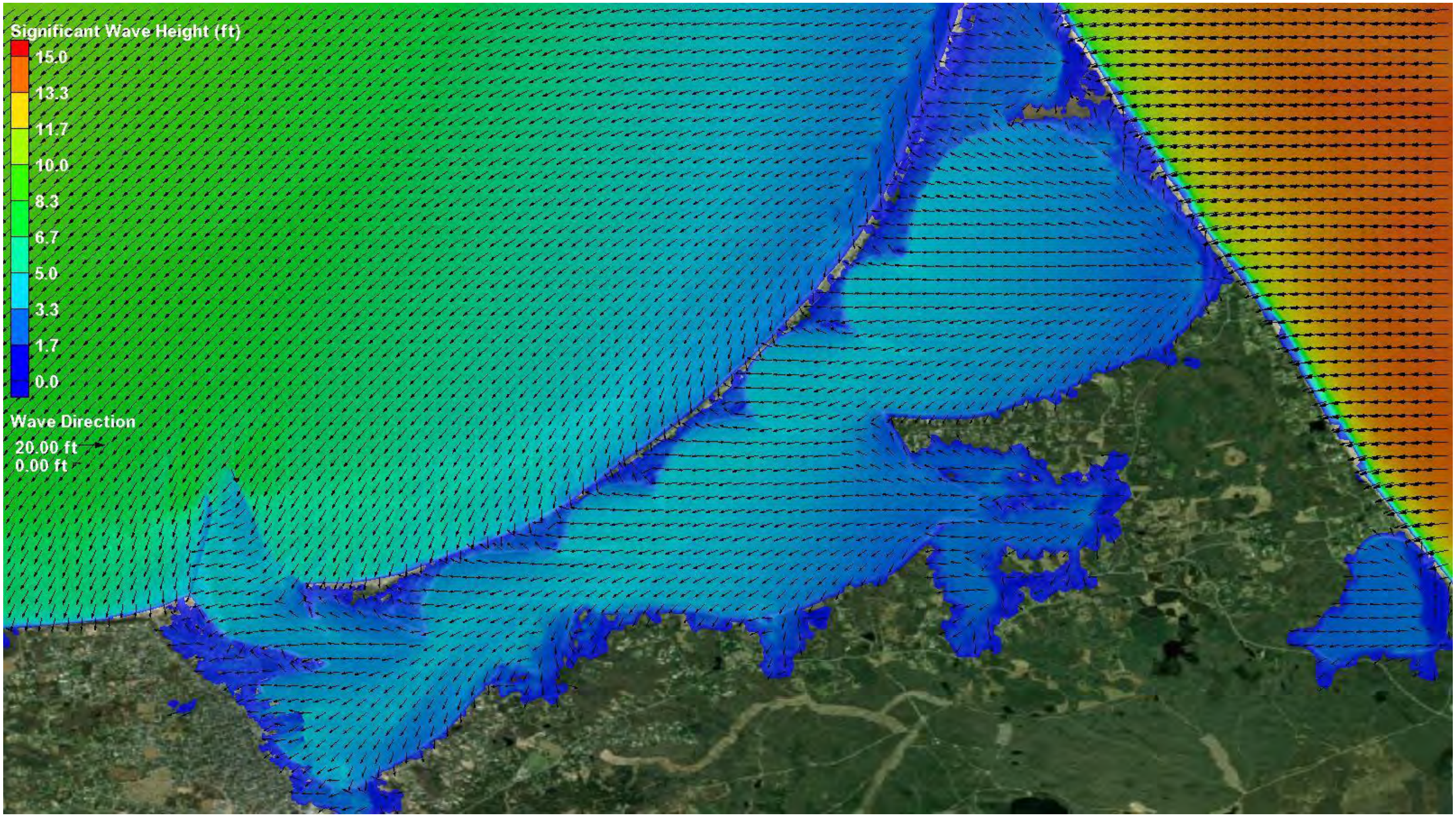

Figure 15: Significant Wave Height simulated by SWAN Wave Model for Run #1 – view 2

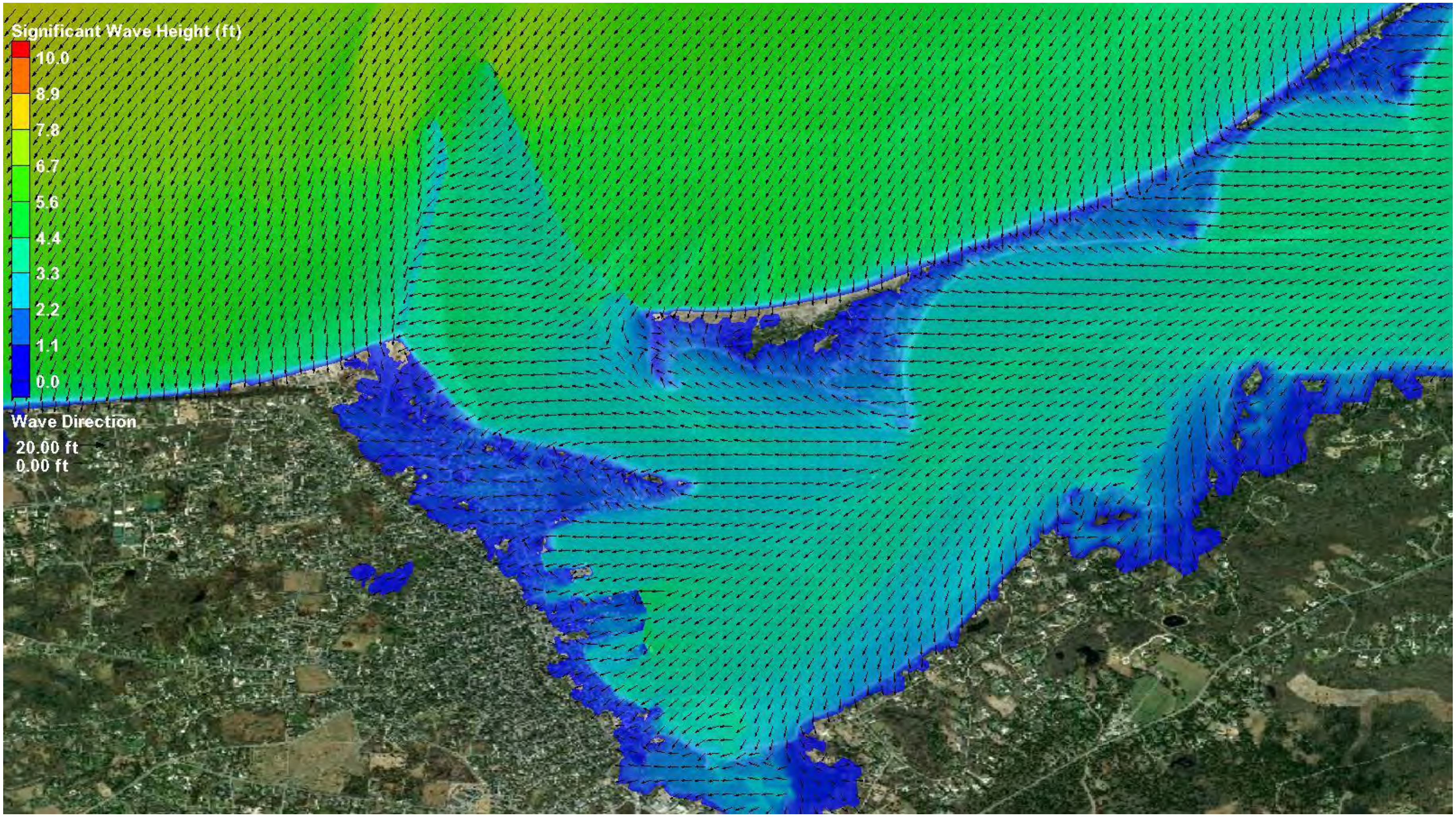

Figure 16: Significant Wave Height simulated by SWAN Wave Model for Run #1 – view 3

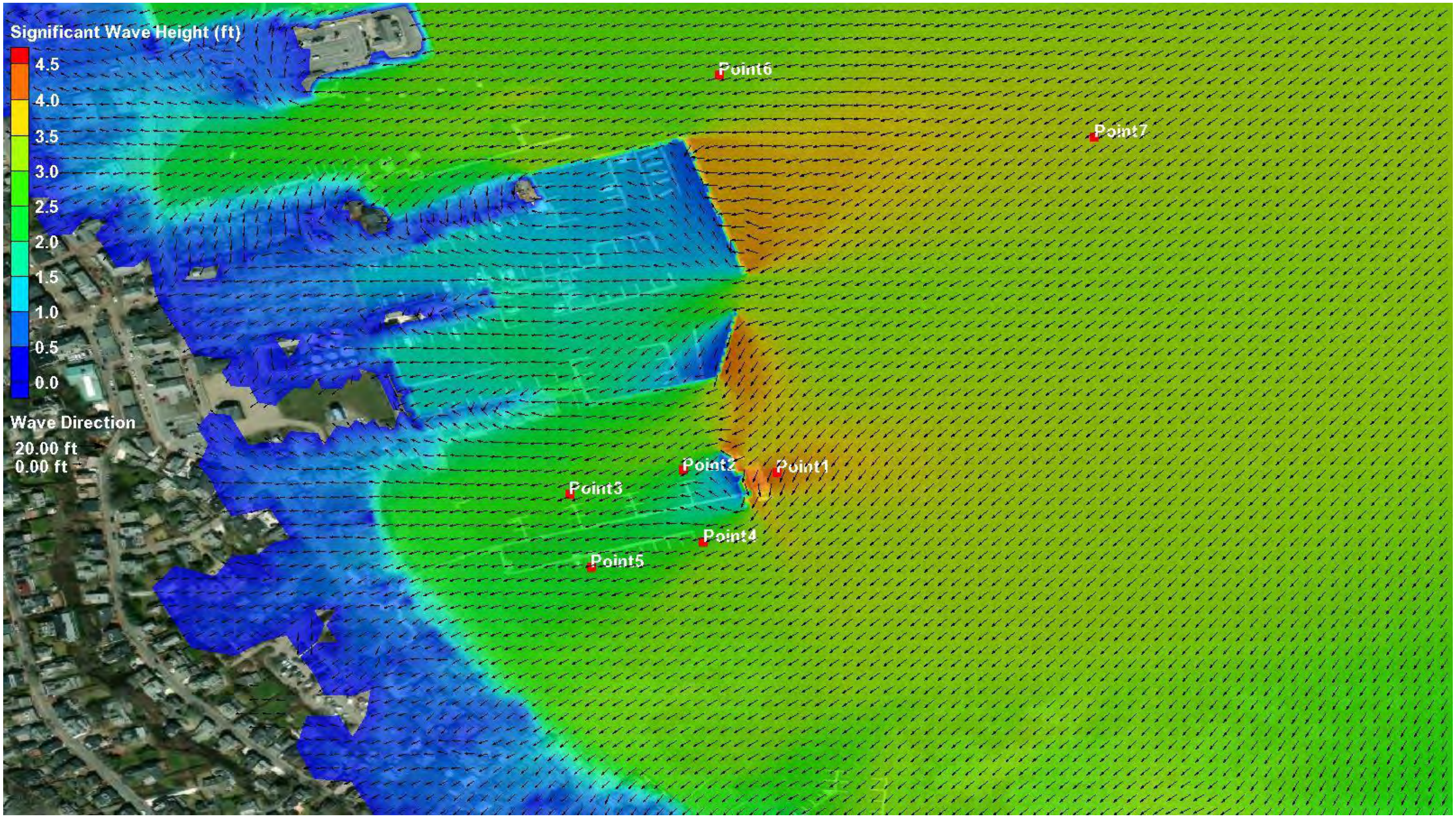

Figure 17: Significant Wave Height simulated by SWAN Wave Model for Run #1 – view 4

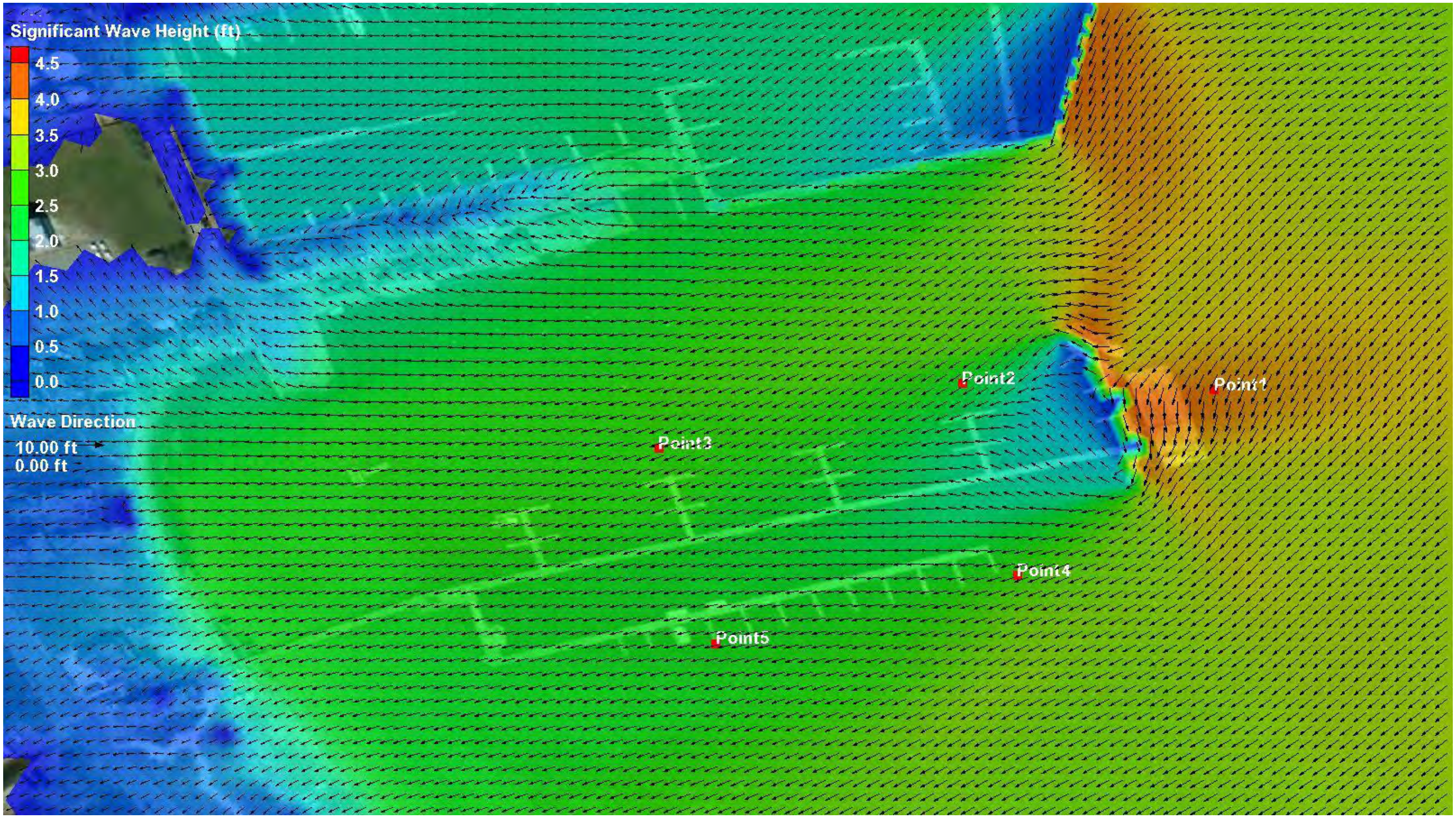

Figure 18: Significant Wave Height simulated by SWAN Wave Model for Run #1 – view 5

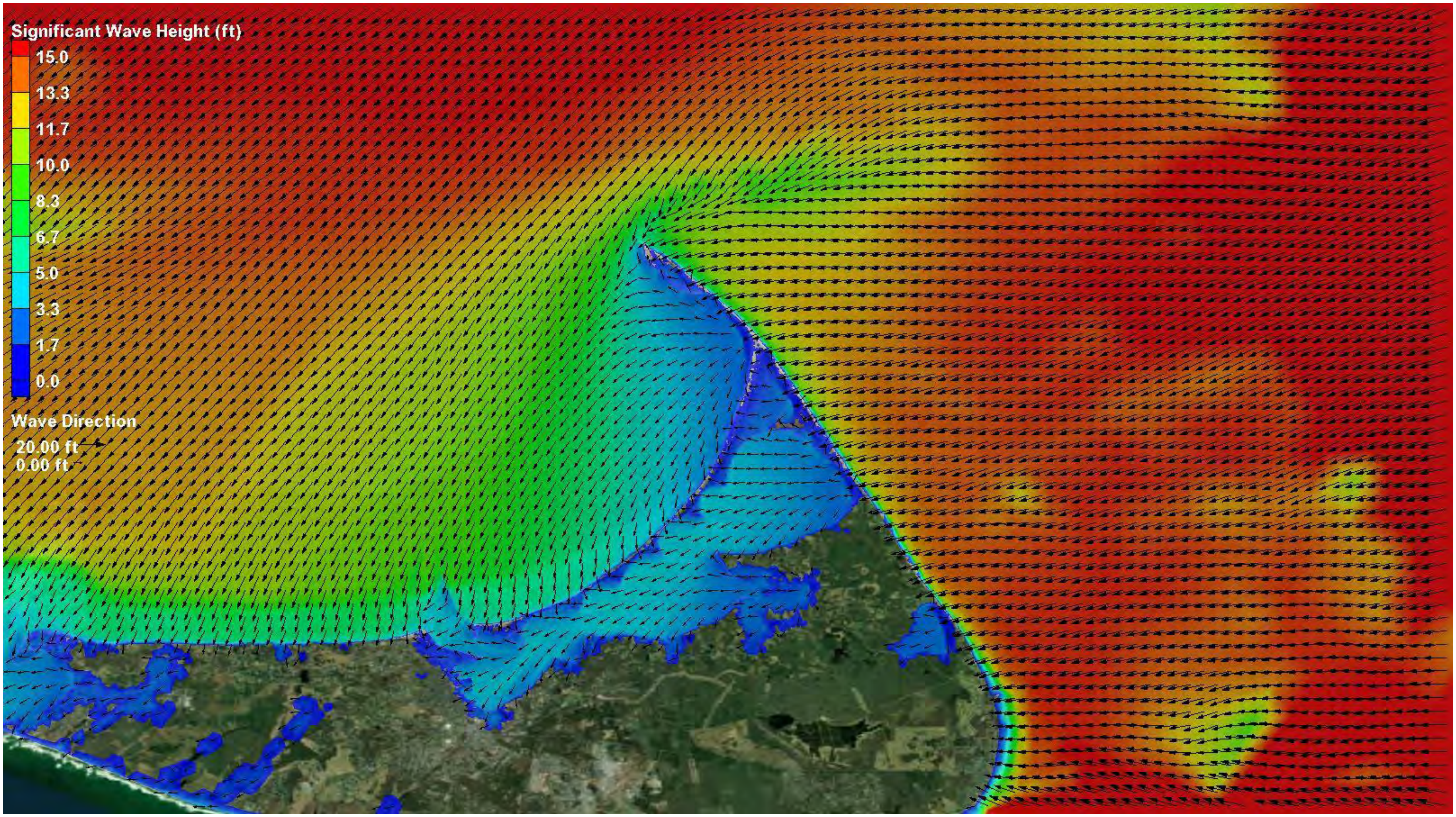

Figure 19: Significant Wave Height simulated by SWAN Wave Model for Run #2 – view 1

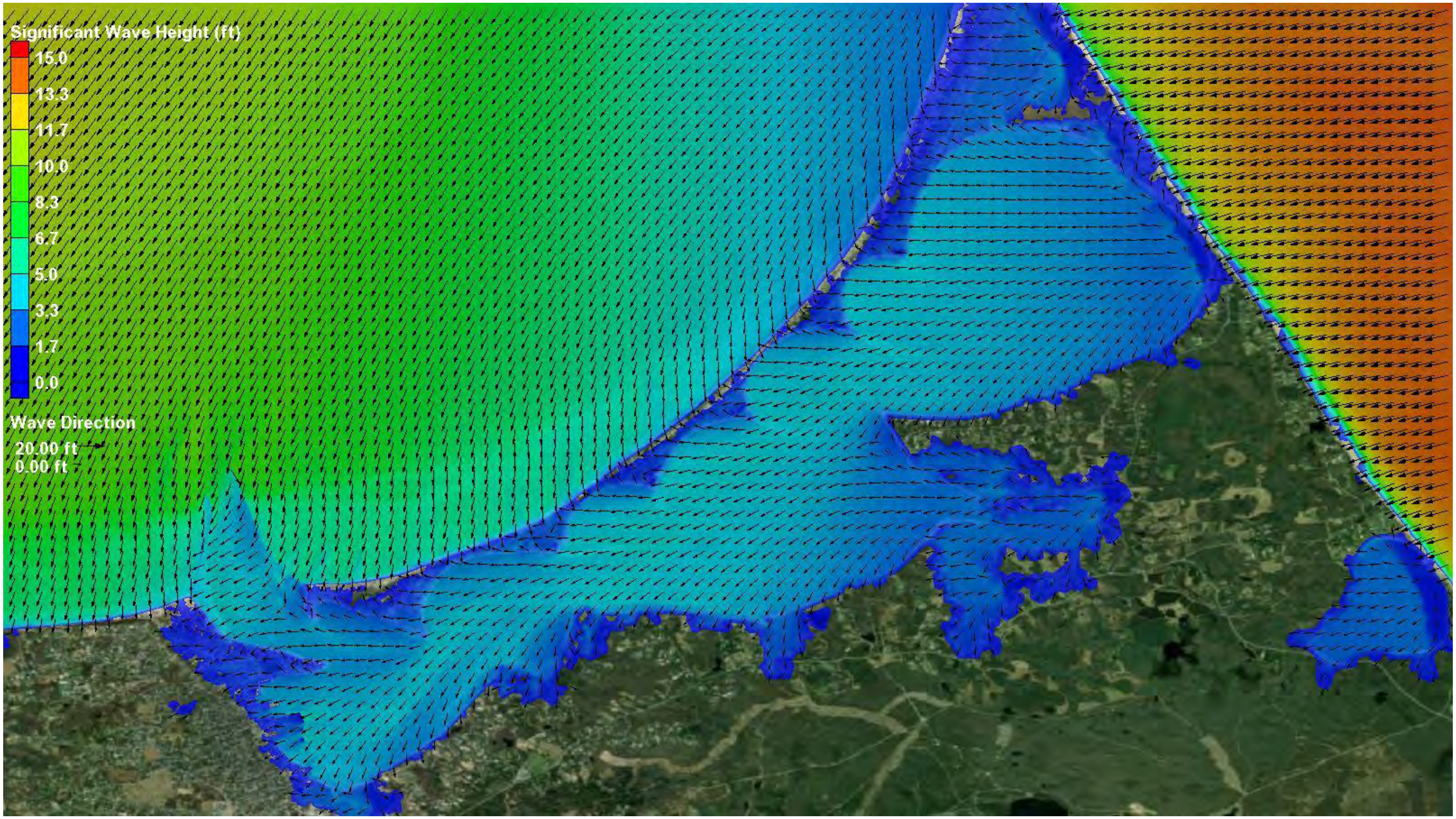

Figure 20: Significant Wave Height simulated by SWAN Wave Model for Run #2 – view 2

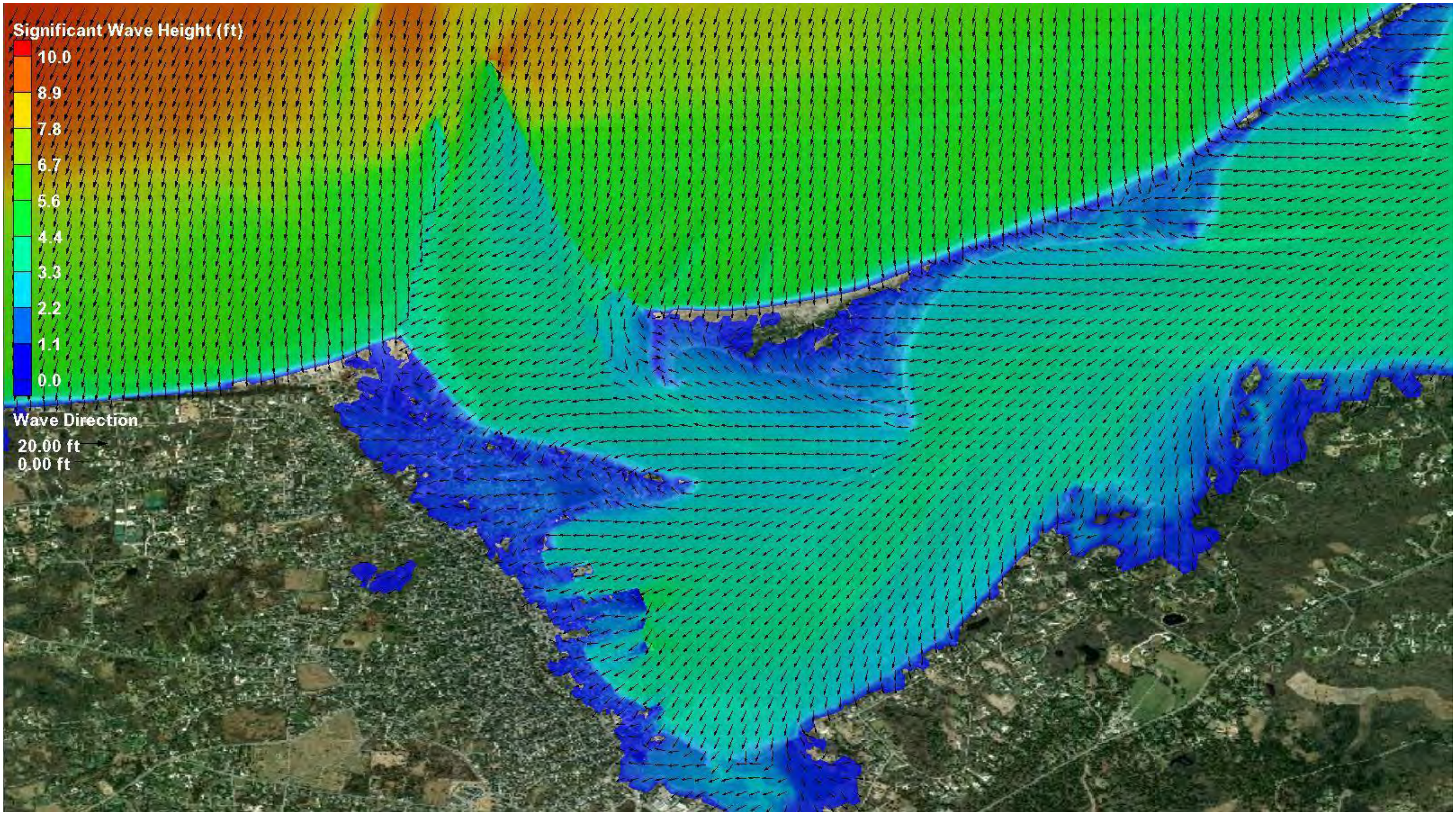

Figure 21: Significant Wave Height simulated by SWAN Wave Model for Run #2 – view 3

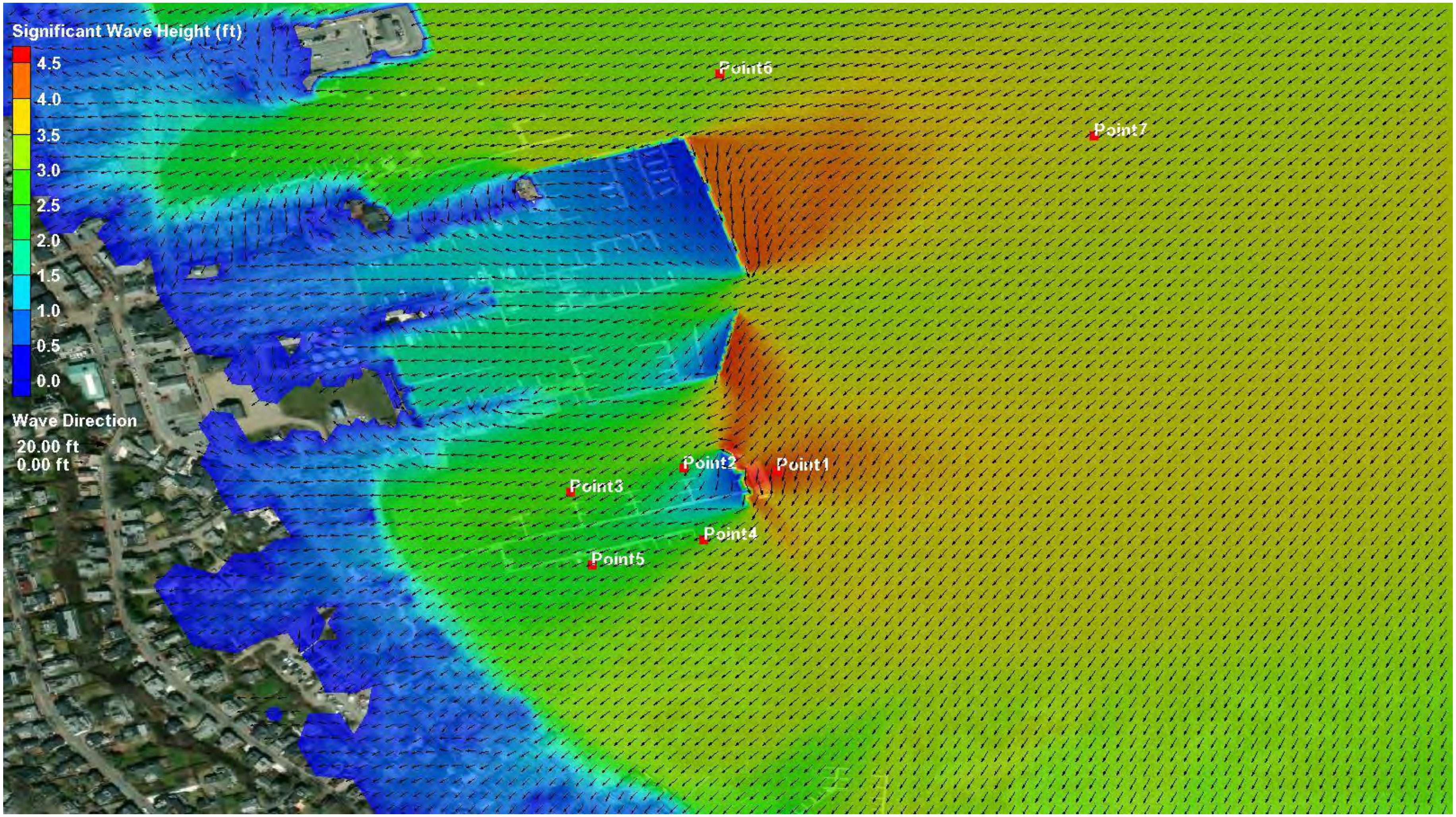

Figure 22: Significant Wave Height simulated by SWAN Wave Model for Run #2 – view 4

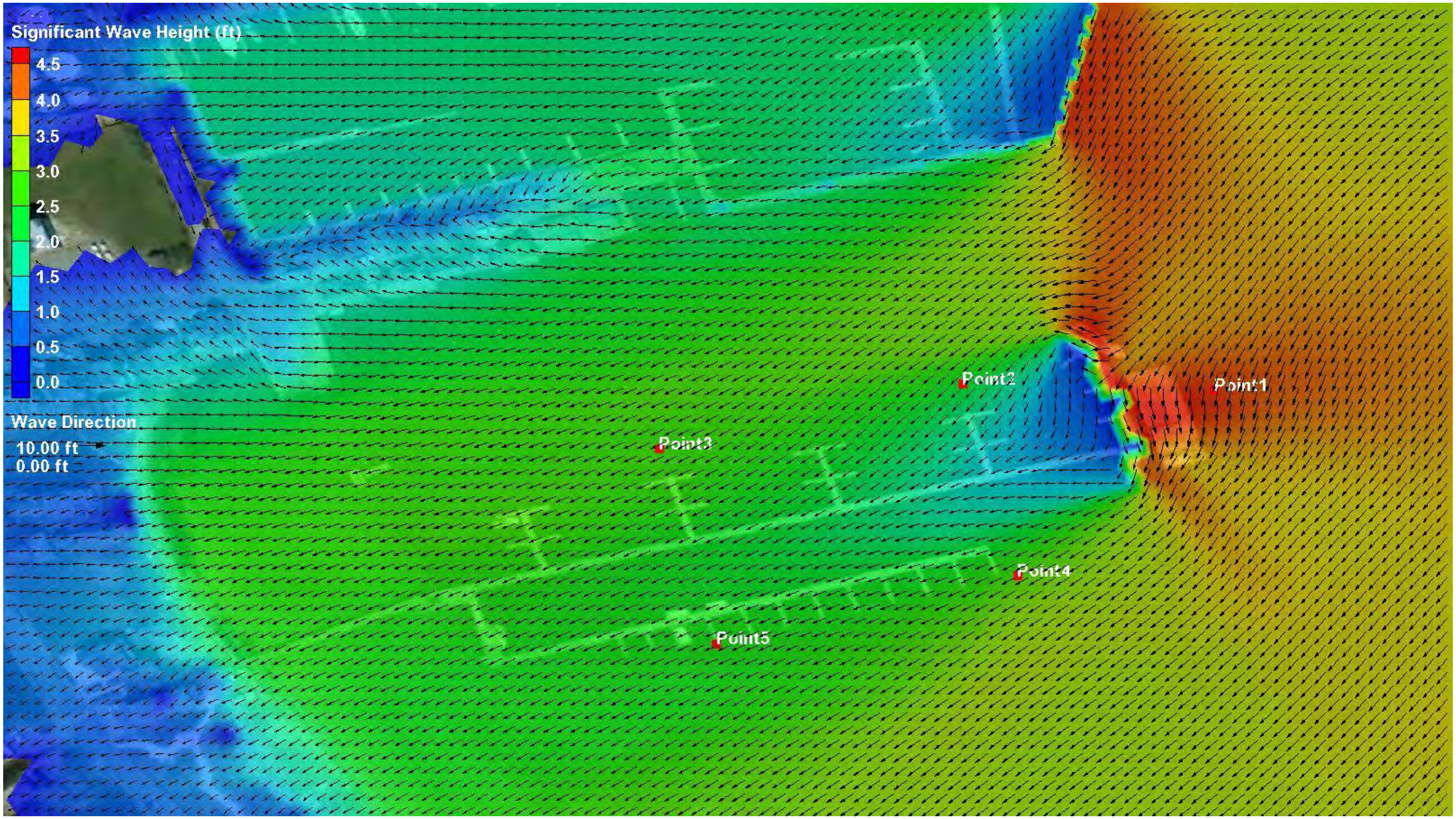

Figure 23: Significant Wave Height simulated by SWAN Wave Model for Run #2 – view 5

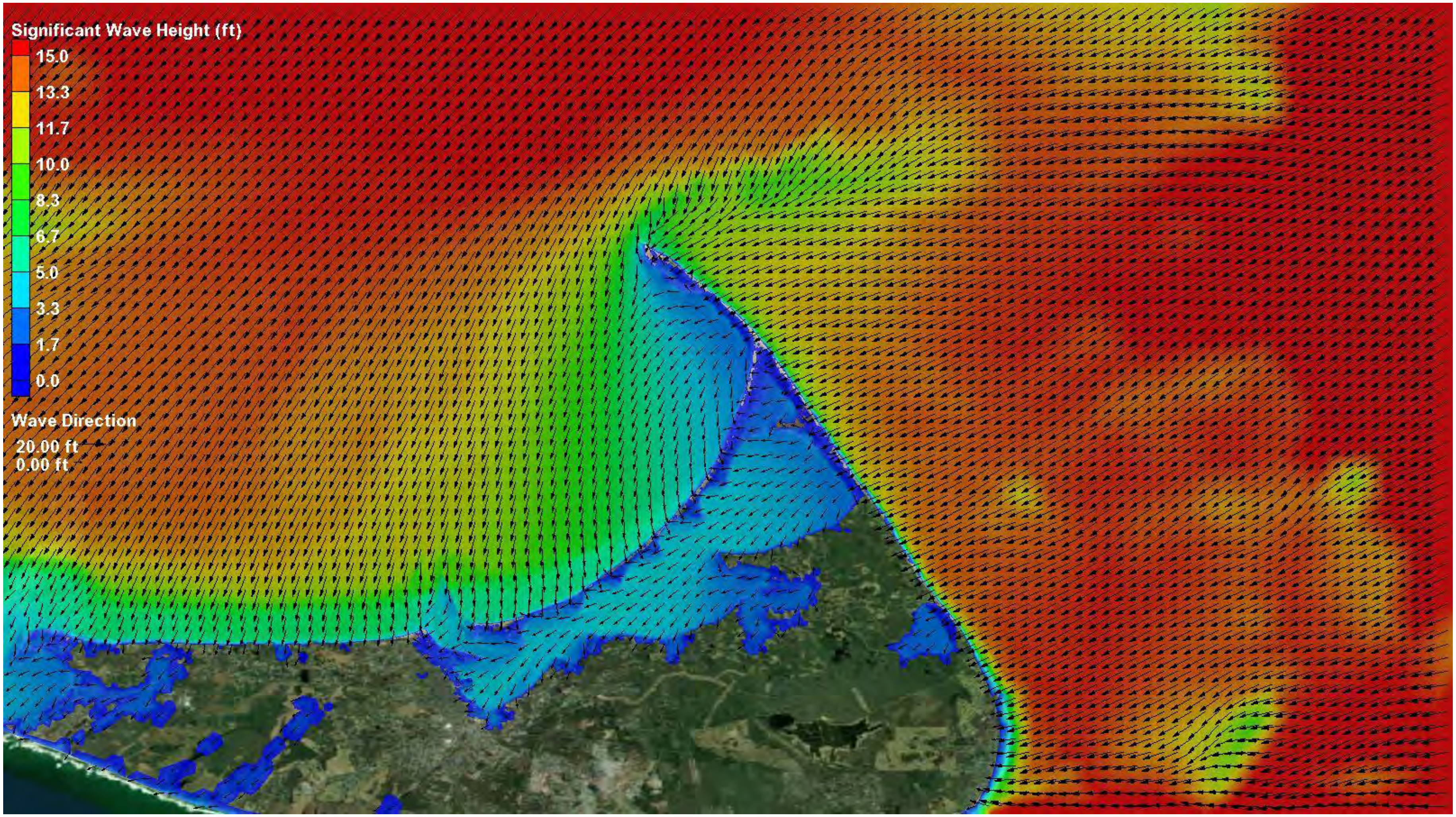

Figure 24: Significant Wave Height simulated by SWAN Wave Model for Run #3 – view 1

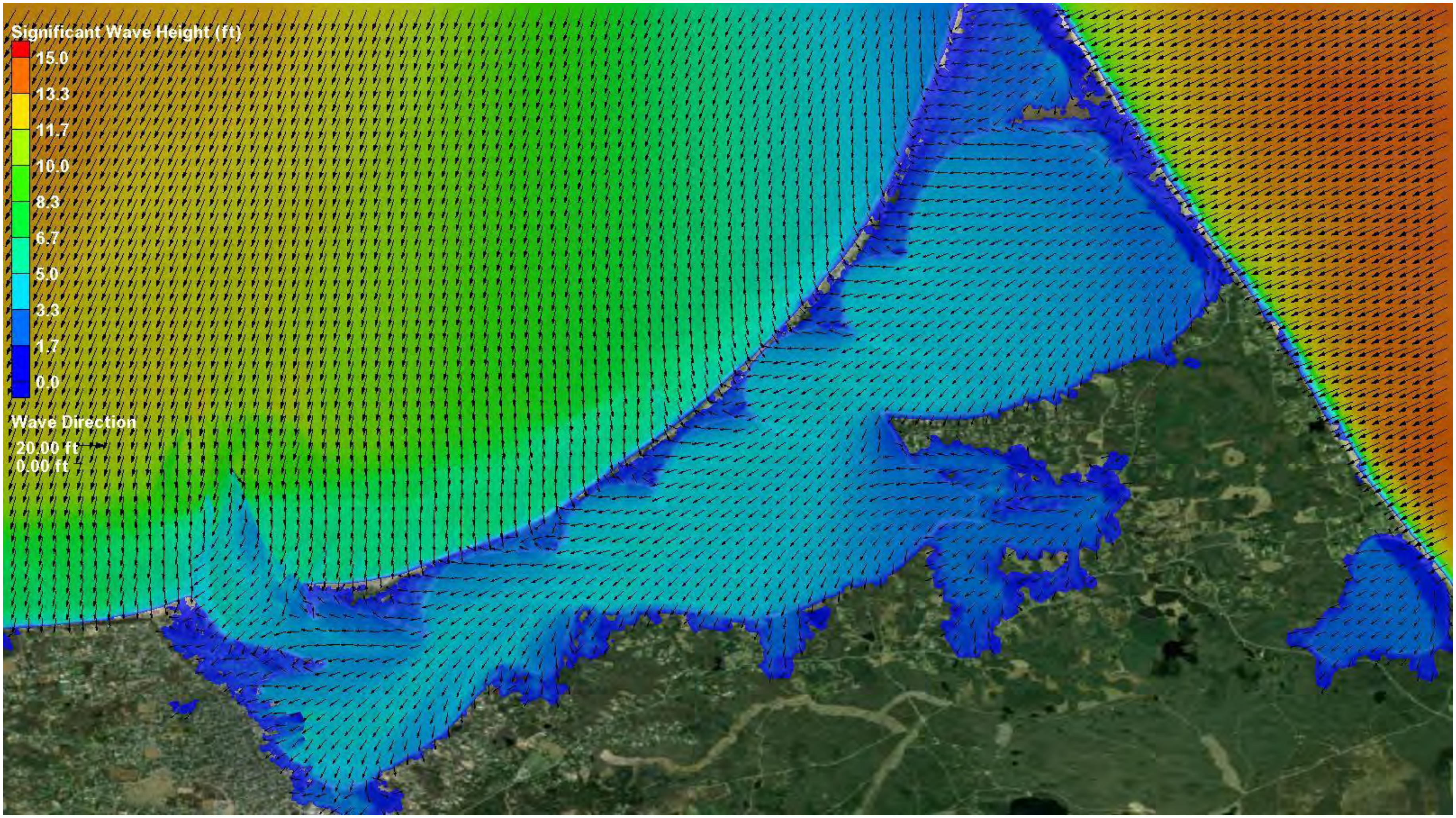

Figure 25: Significant Wave Height simulated by SWAN Wave Model for Run #3 – view 2

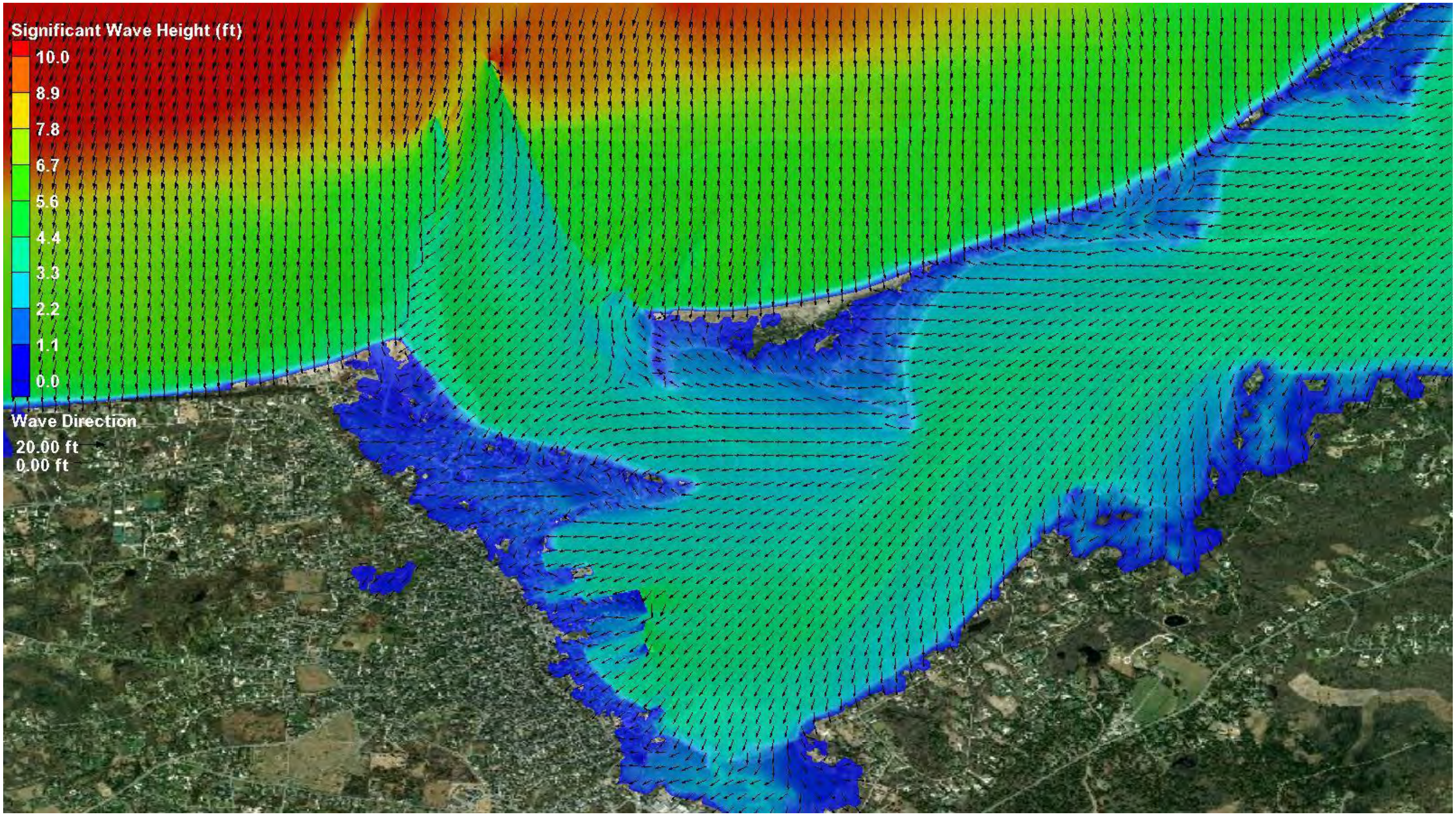

Figure 26: Significant Wave Height simulated by SWAN Wave Model for Run #3 – view 3

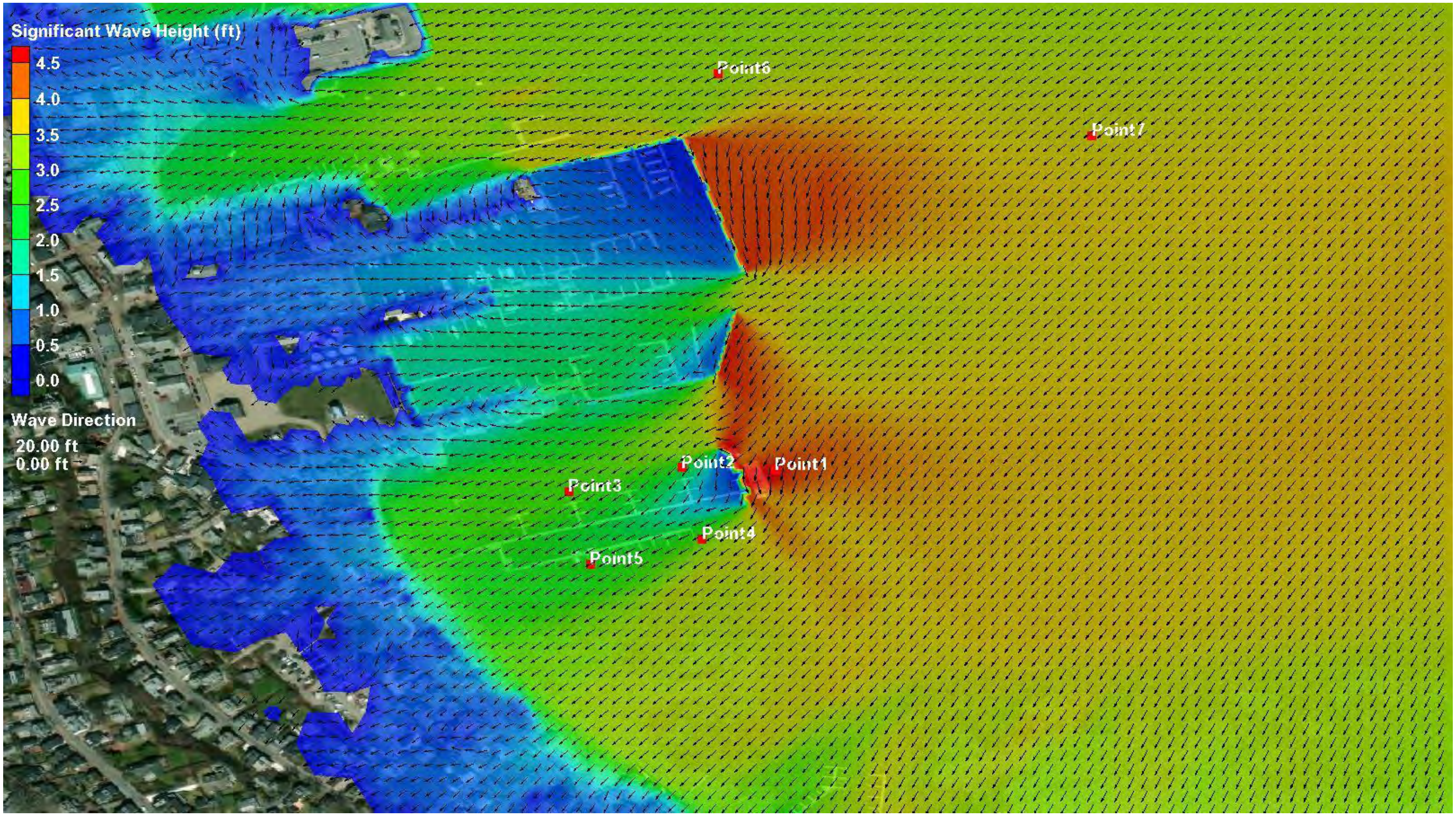

Figure 27: Significant Wave Height simulated by SWAN Wave Model for Run #3 – view 4

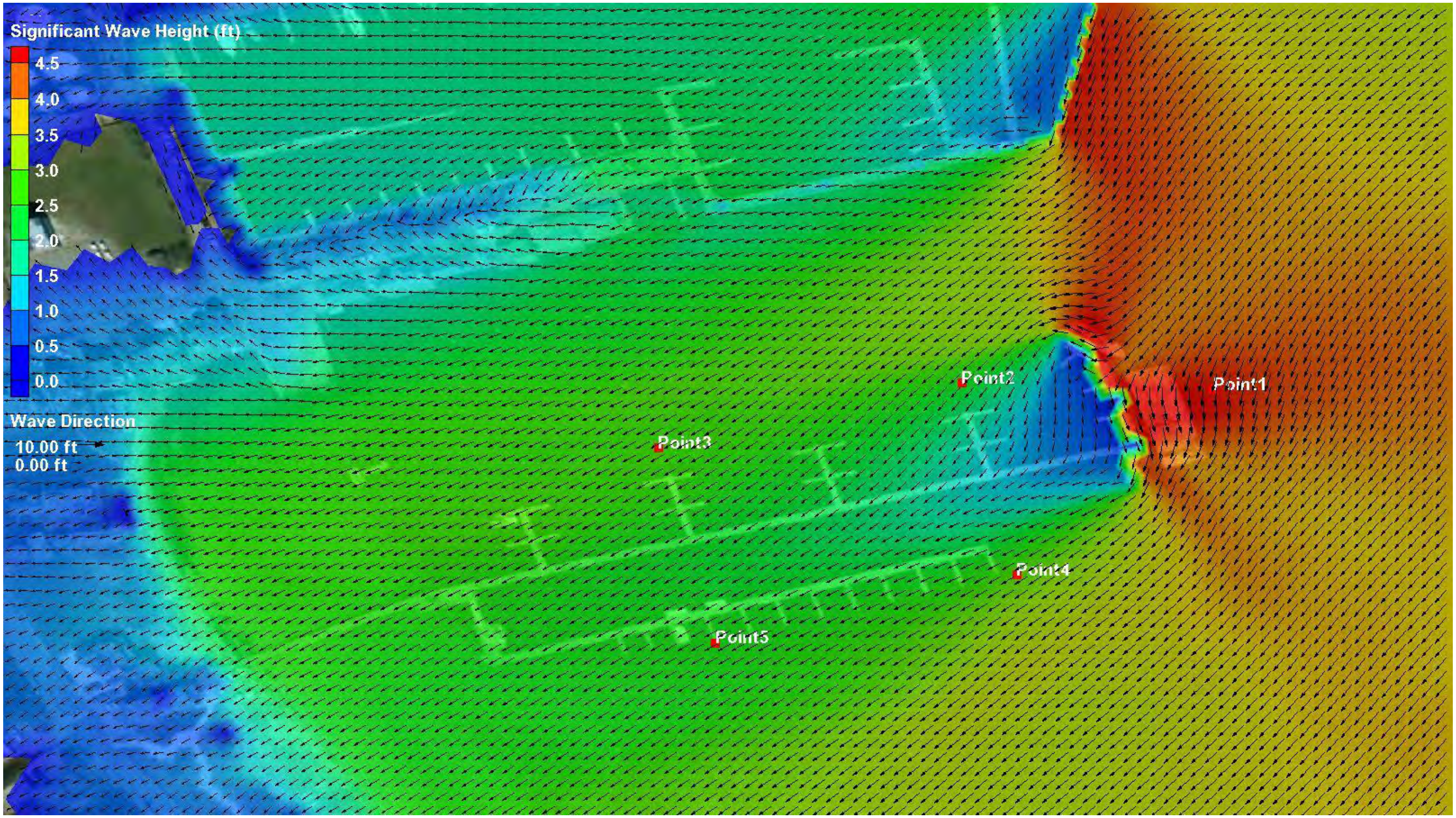

Figure 28: Significant Wave Height simulated by SWAN Wave Model for Run #3 – view 5

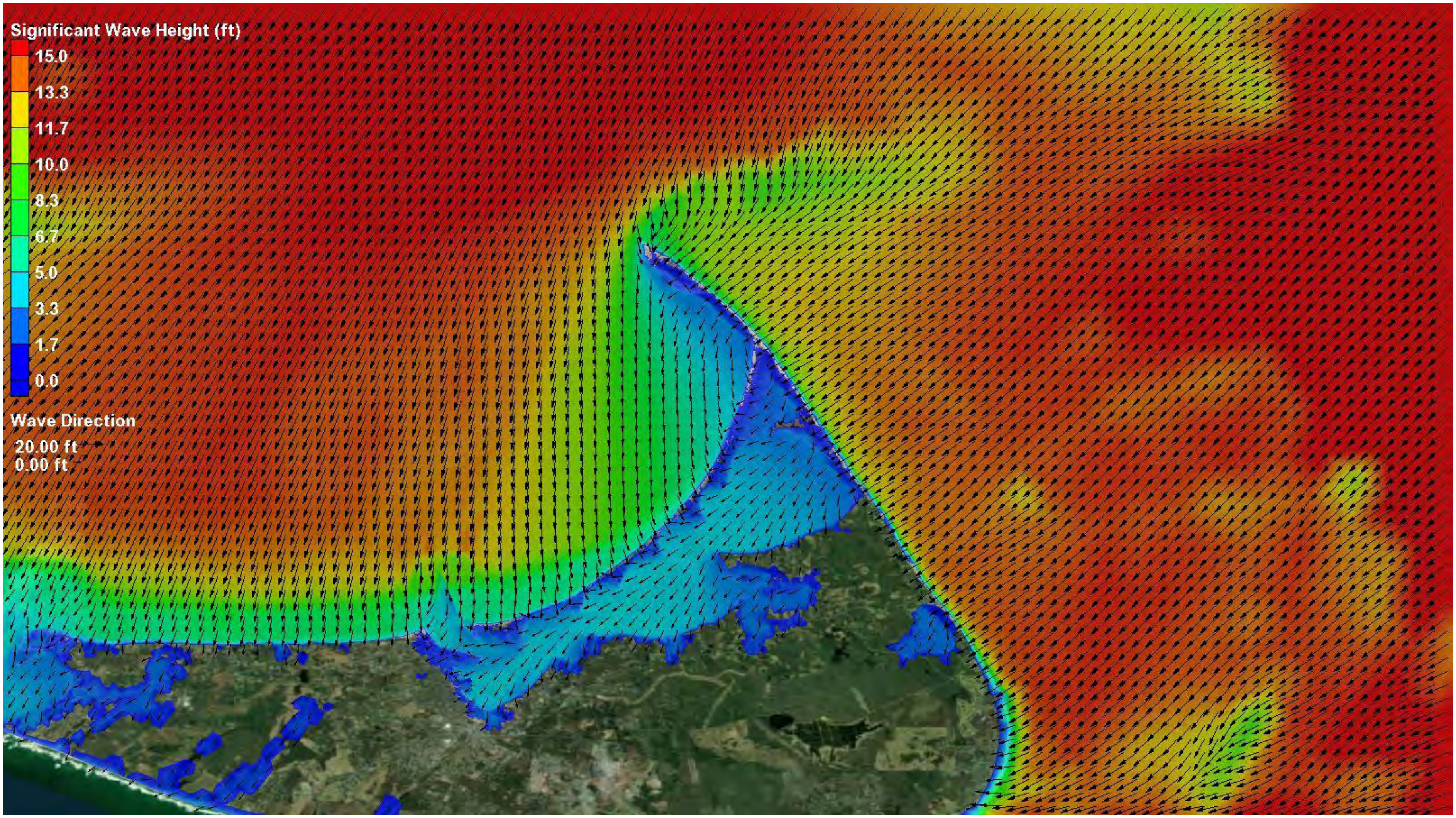

Figure 29: Significant Wave Height simulated by SWAN Wave Model for Run #4 – view 1

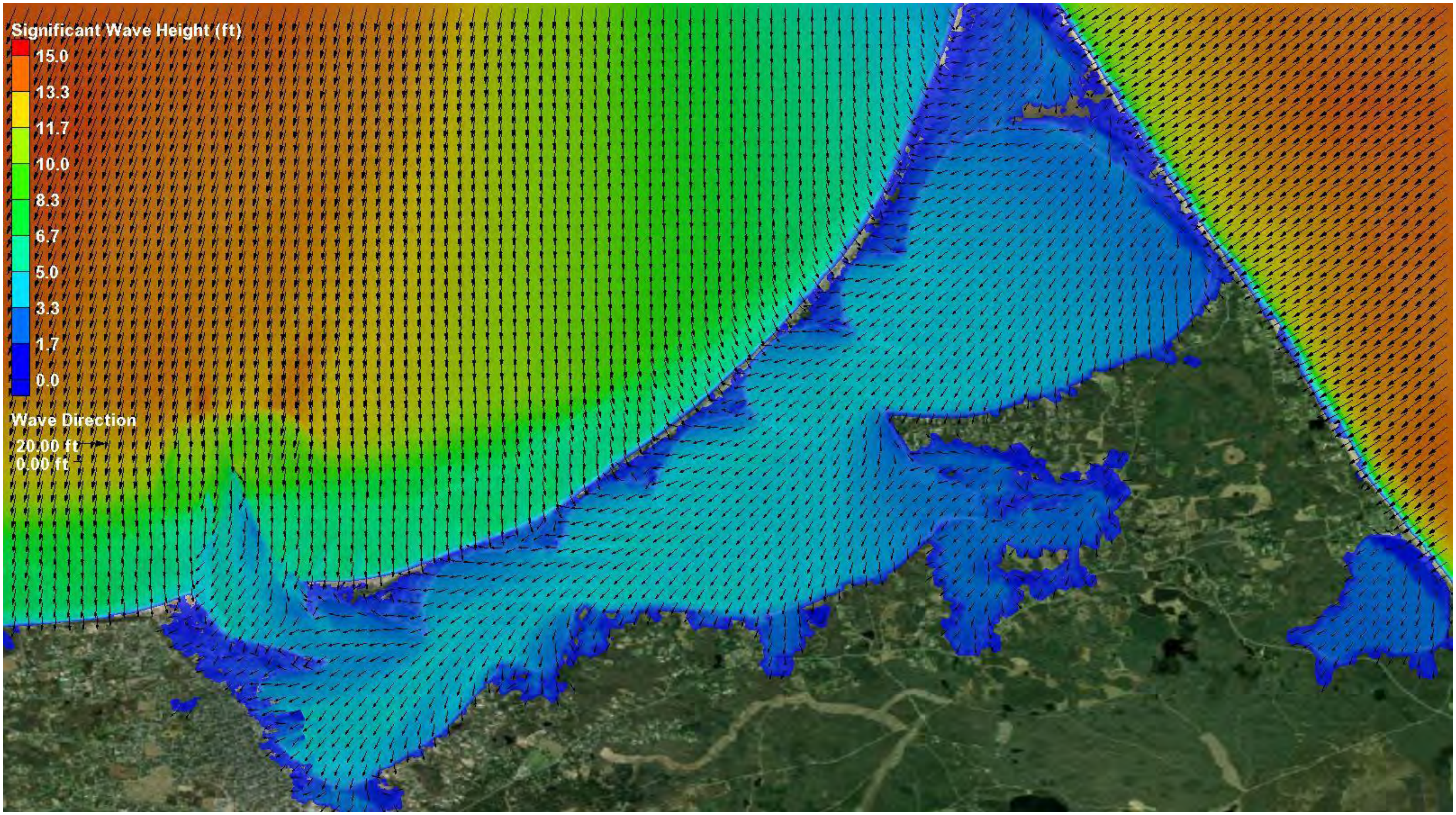

Figure 30: Significant Wave Height simulated by SWAN Wave Model for Run #4 – view 2

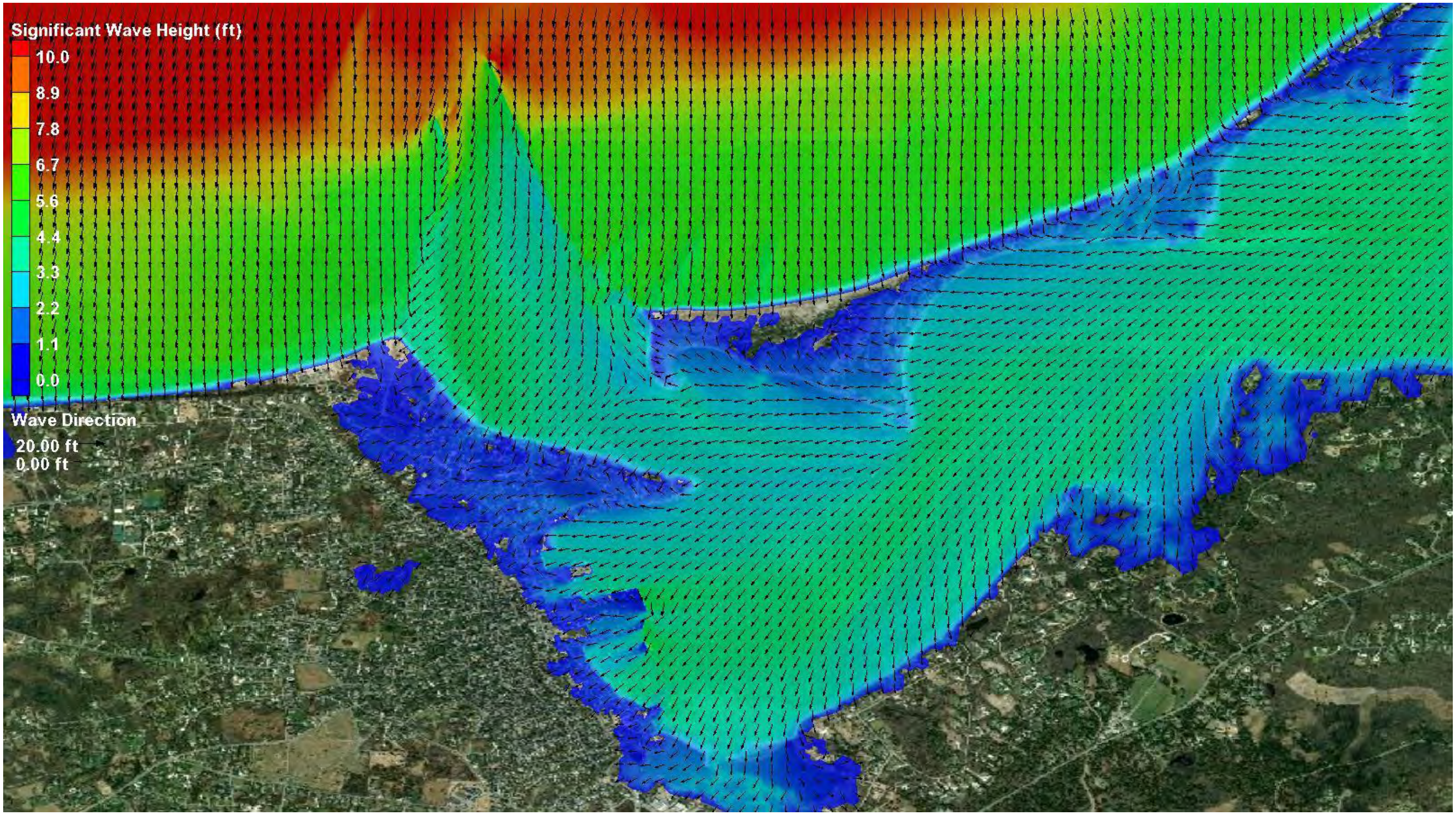

Figure 31: Significant Wave Height simulated by SWAN Wave Model for Run #4 – view 3

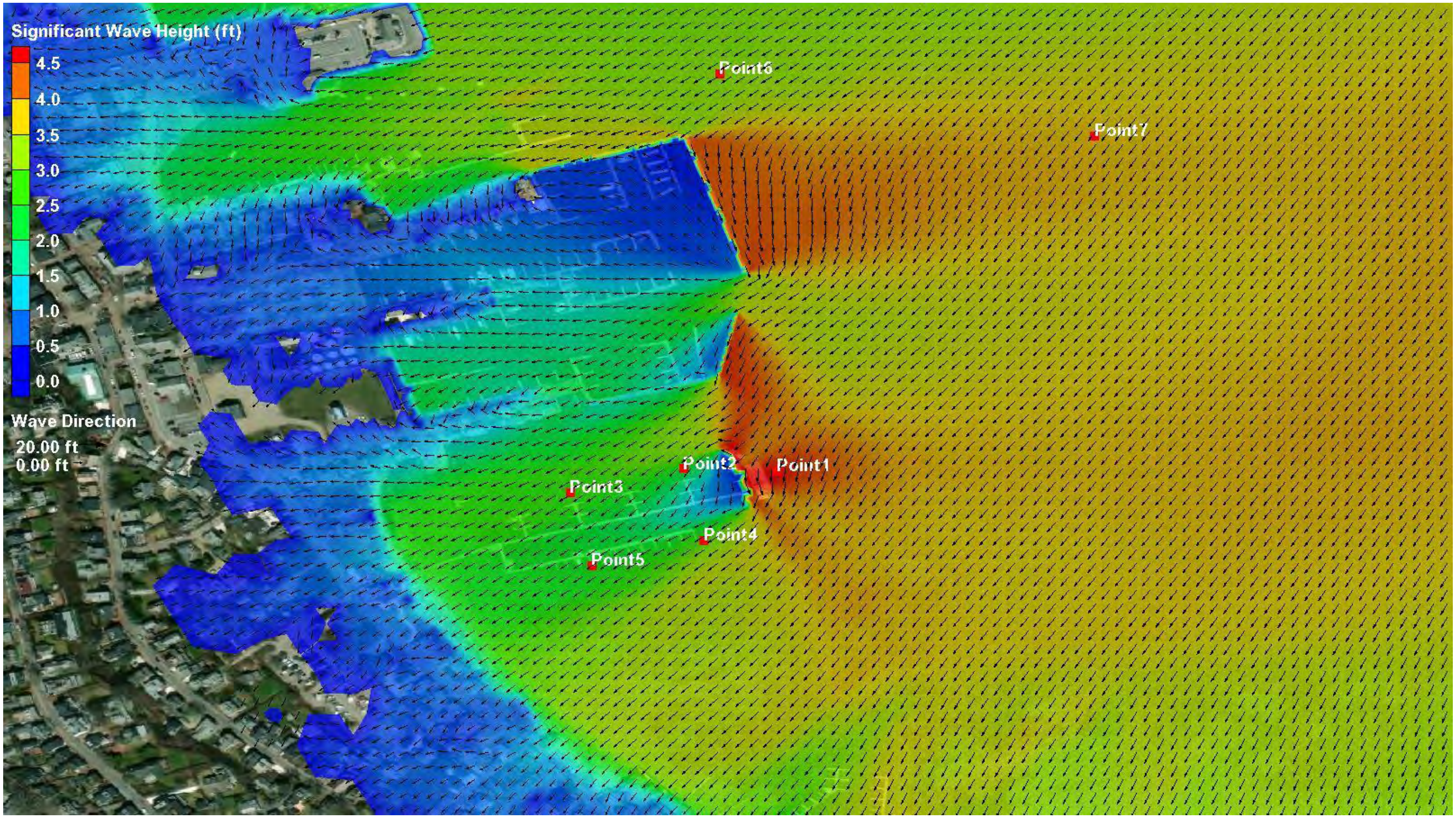

Figure 32: Significant Wave Height simulated by SWAN Wave Model for Run #4 – view 4

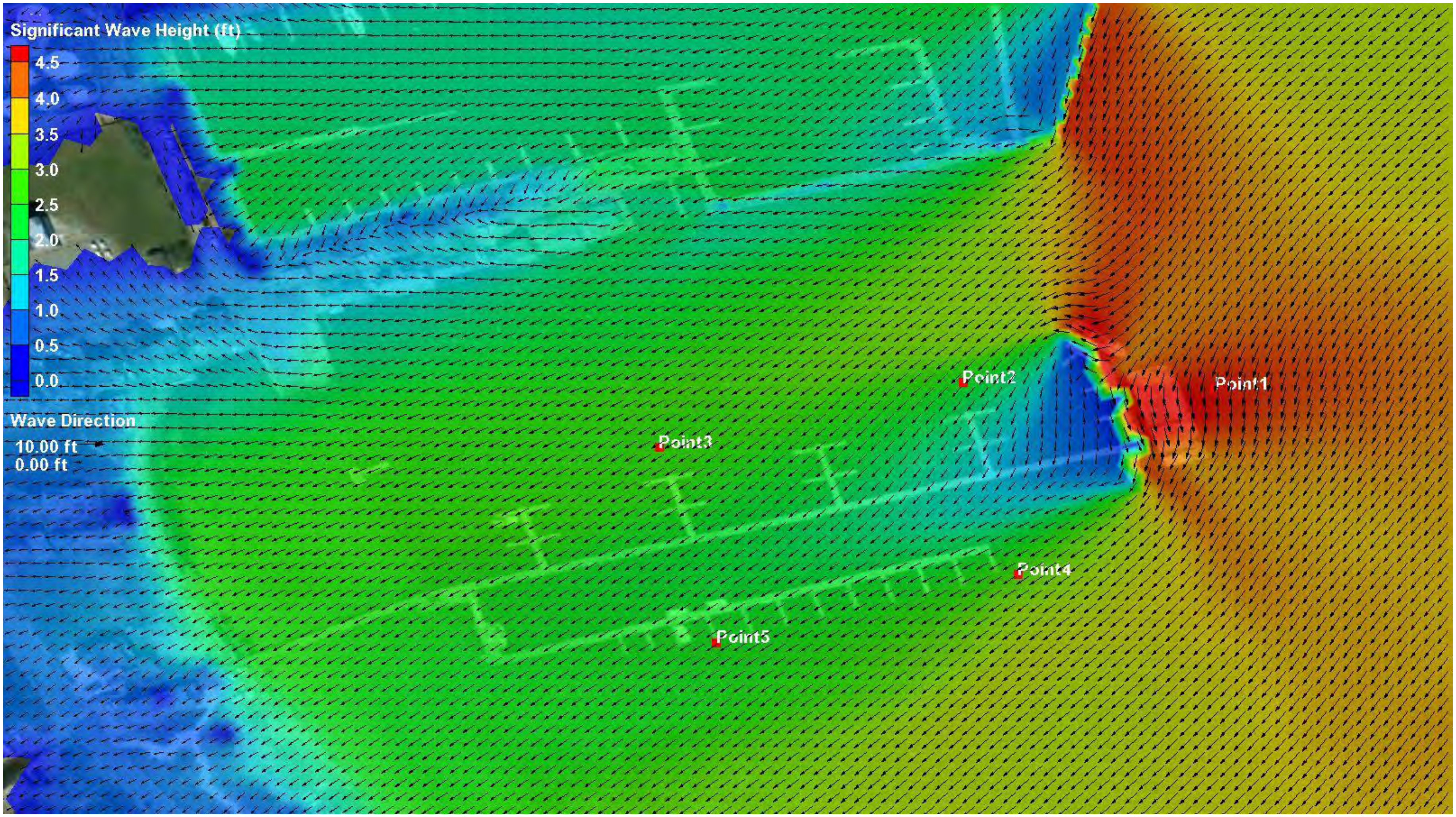

Figure 33: Significant Wave Height simulated by SWAN Wave Model for Run #4 – view 5

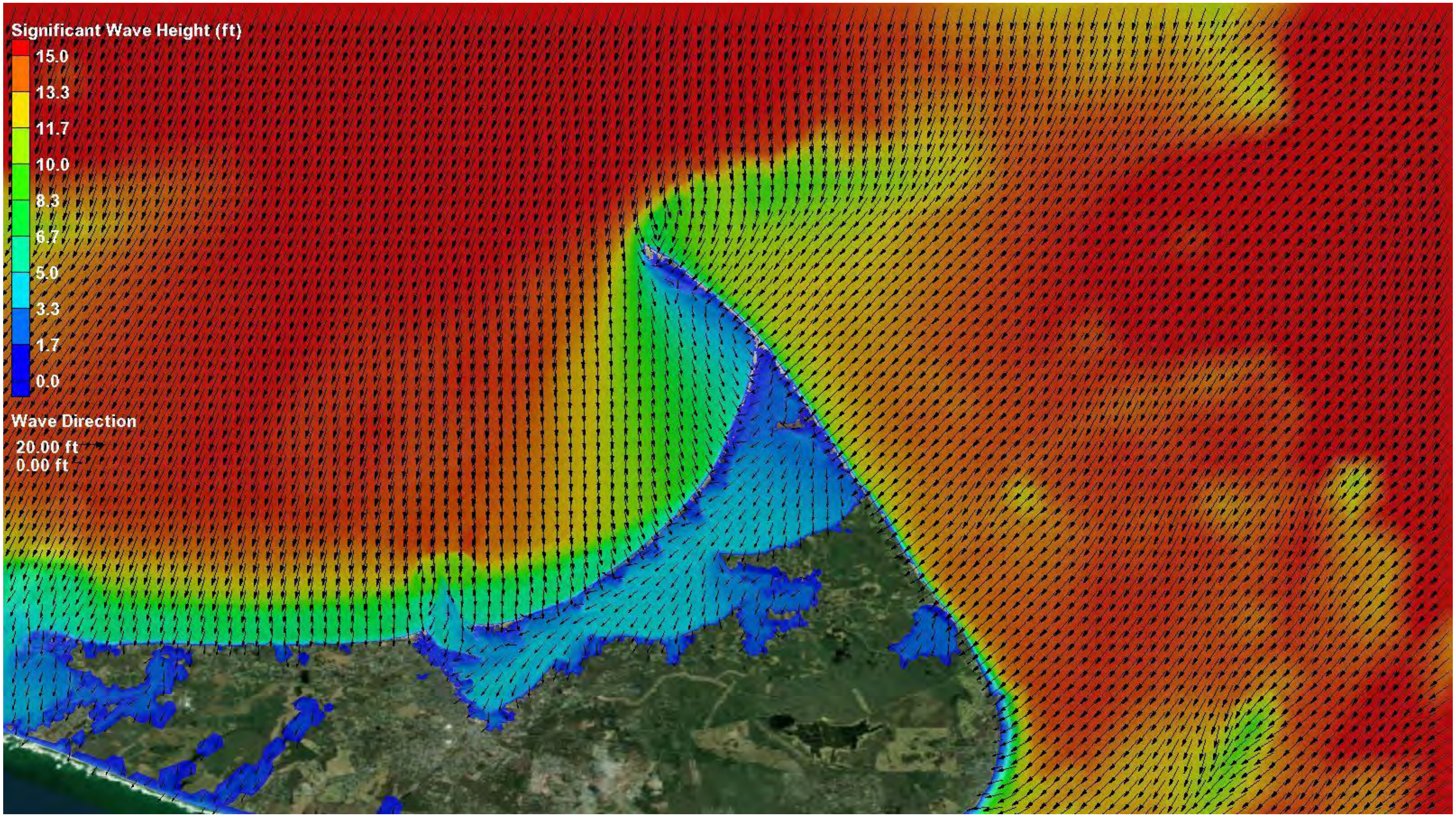

Figure 34: Significant Wave Height simulated by SWAN Wave Model for Run #5 – view 1

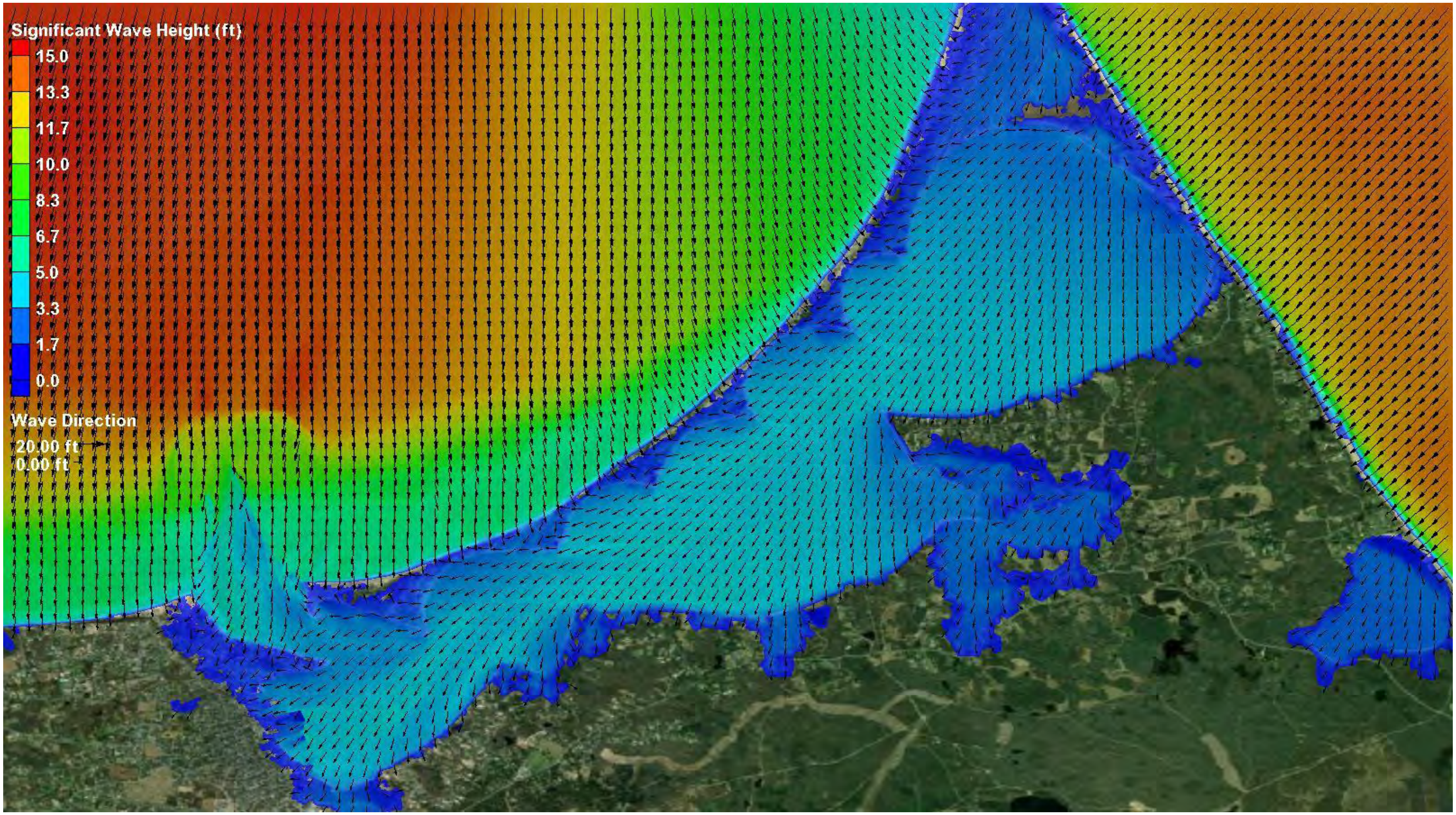

Figure 35: Significant Wave Height simulated by SWAN Wave Model for Run #5 – view 2

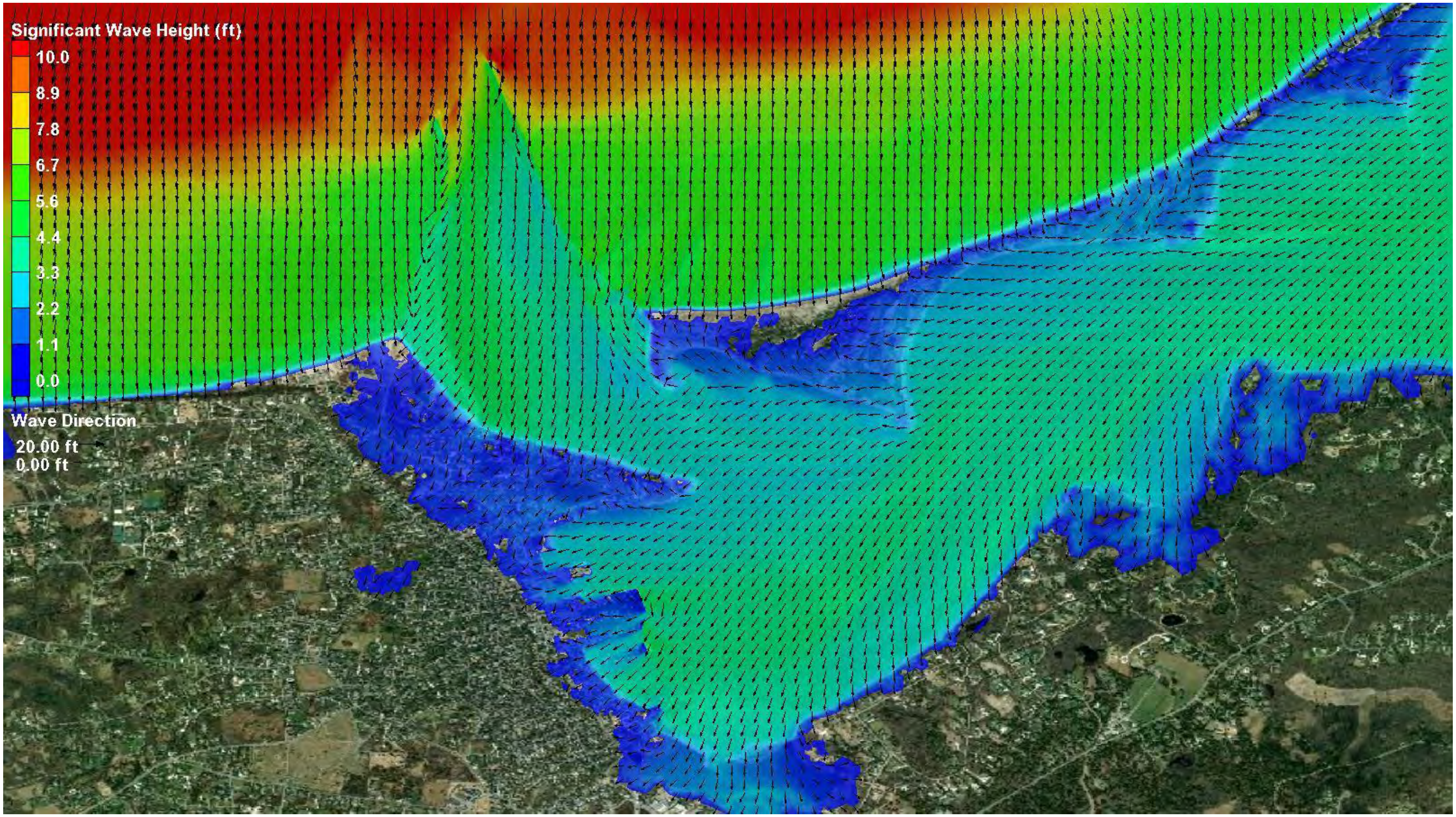

Figure 36: Significant Wave Height simulated by SWAN Wave Model for Run #5 – view 3

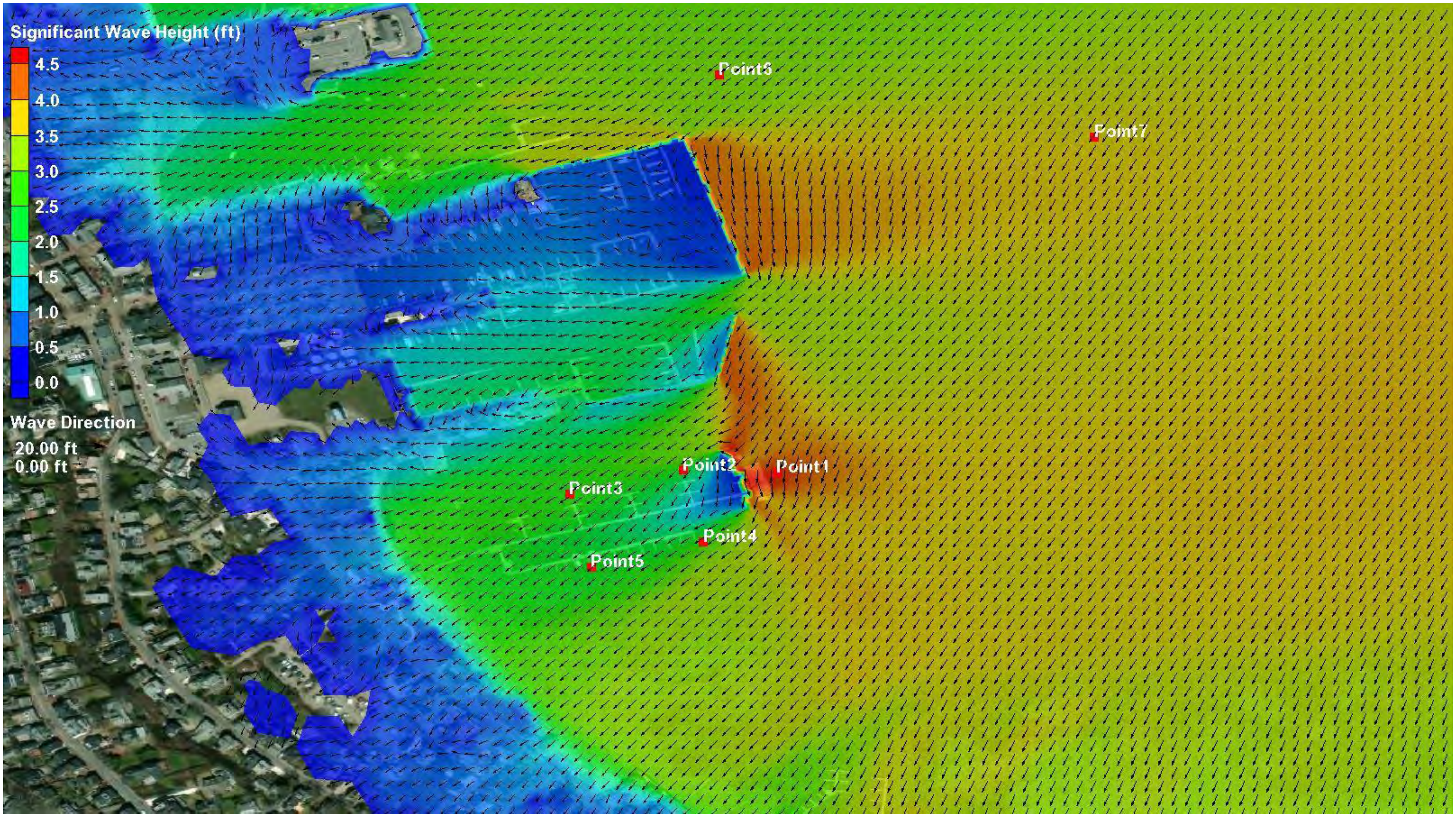

Figure 37: Significant Wave Height simulated by SWAN Wave Model for Run #5 – view 4

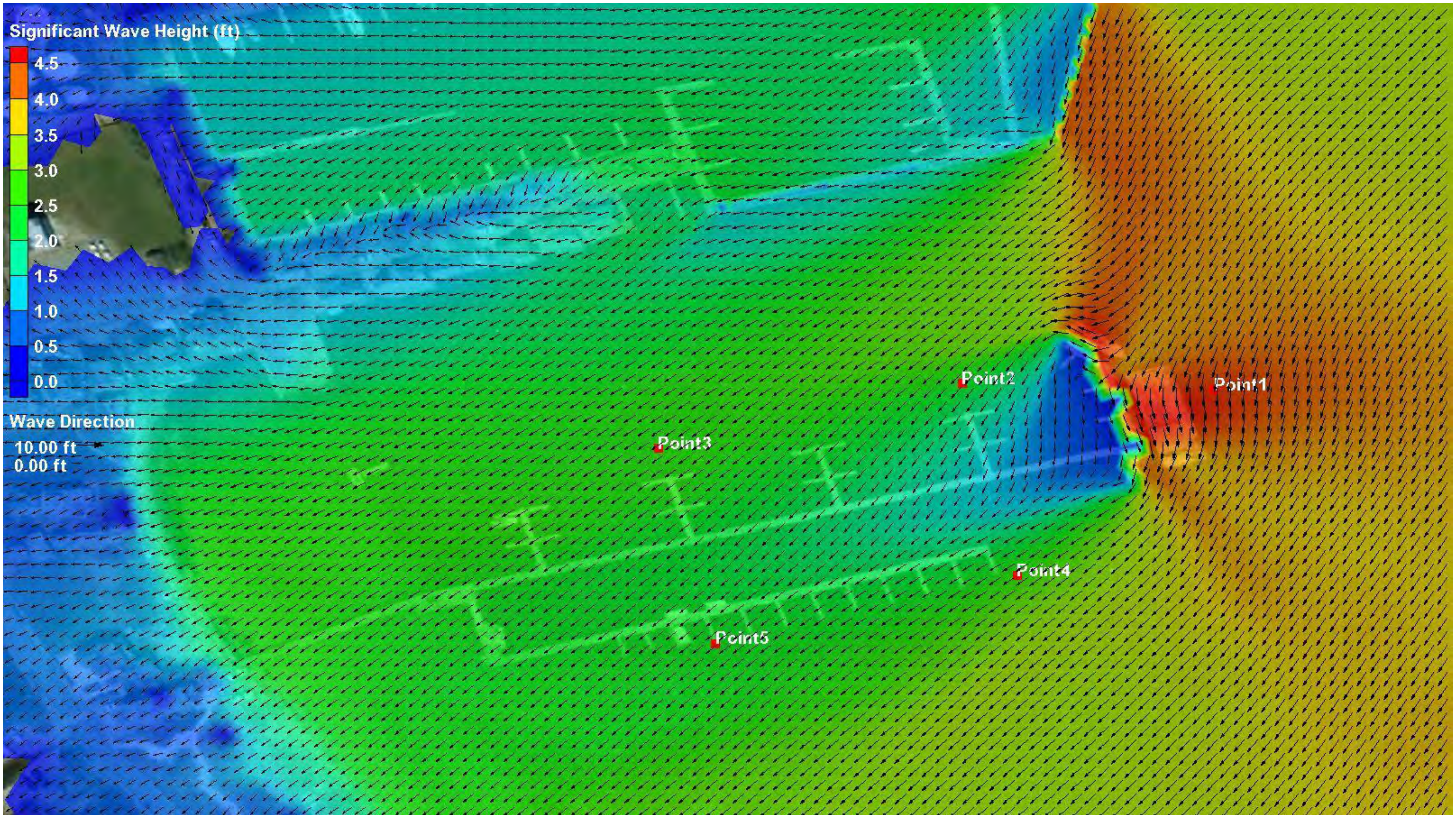

Figure 38: Significant Wave Height simulated by SWAN Wave Model for Run #5 – view 5

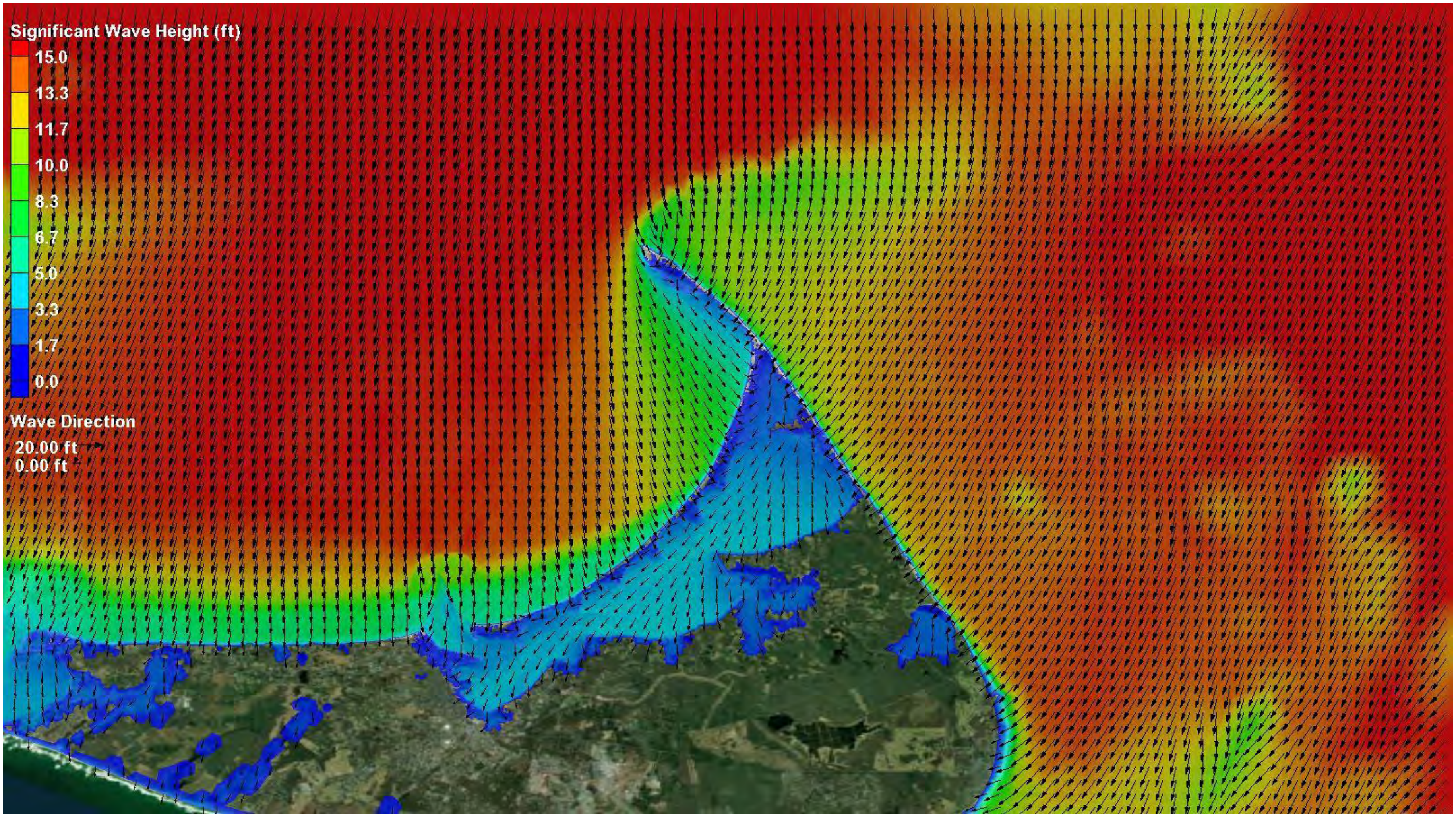

Figure 39: Significant Wave Height simulated by SWAN Wave Model for Run #6 – view 1

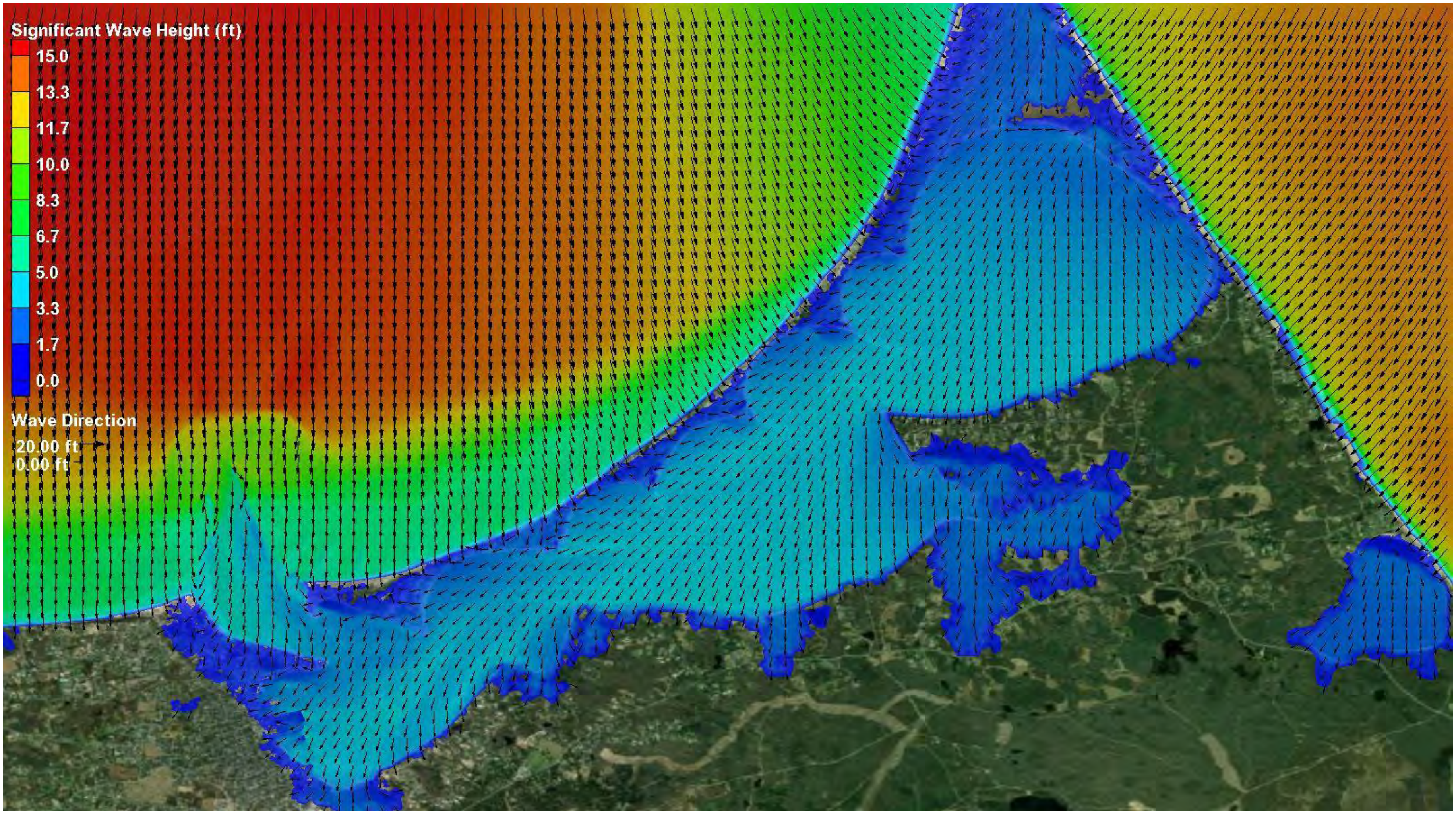

Figure 40: Significant Wave Height simulated by SWAN Wave Model for Run #6 – view 2

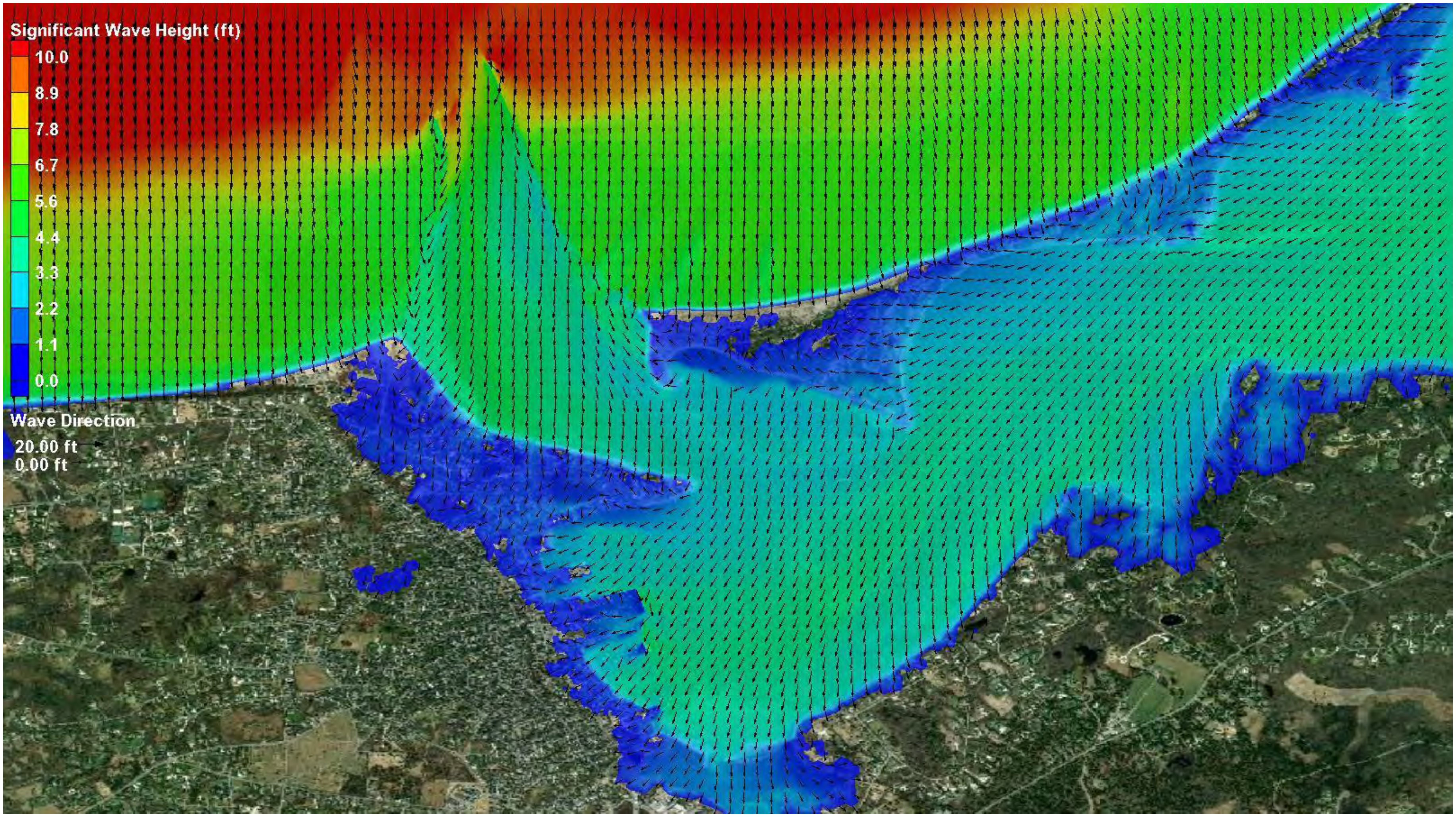

Figure 41: Significant Wave Height simulated by SWAN Wave Model for Run #6 – view 3

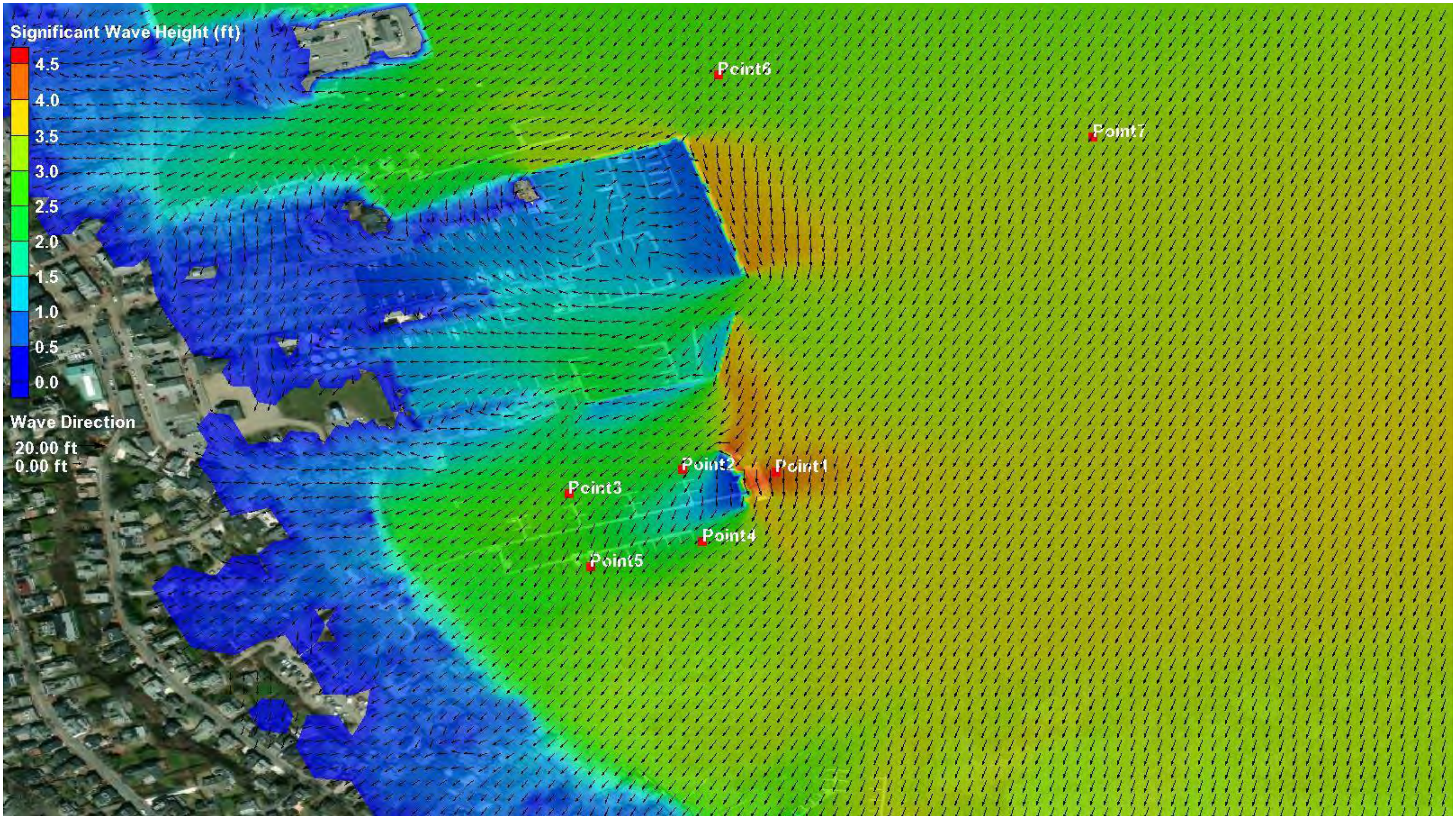

Figure 42: Significant Wave Height simulated by SWAN Wave Model for Run #6 – view 4

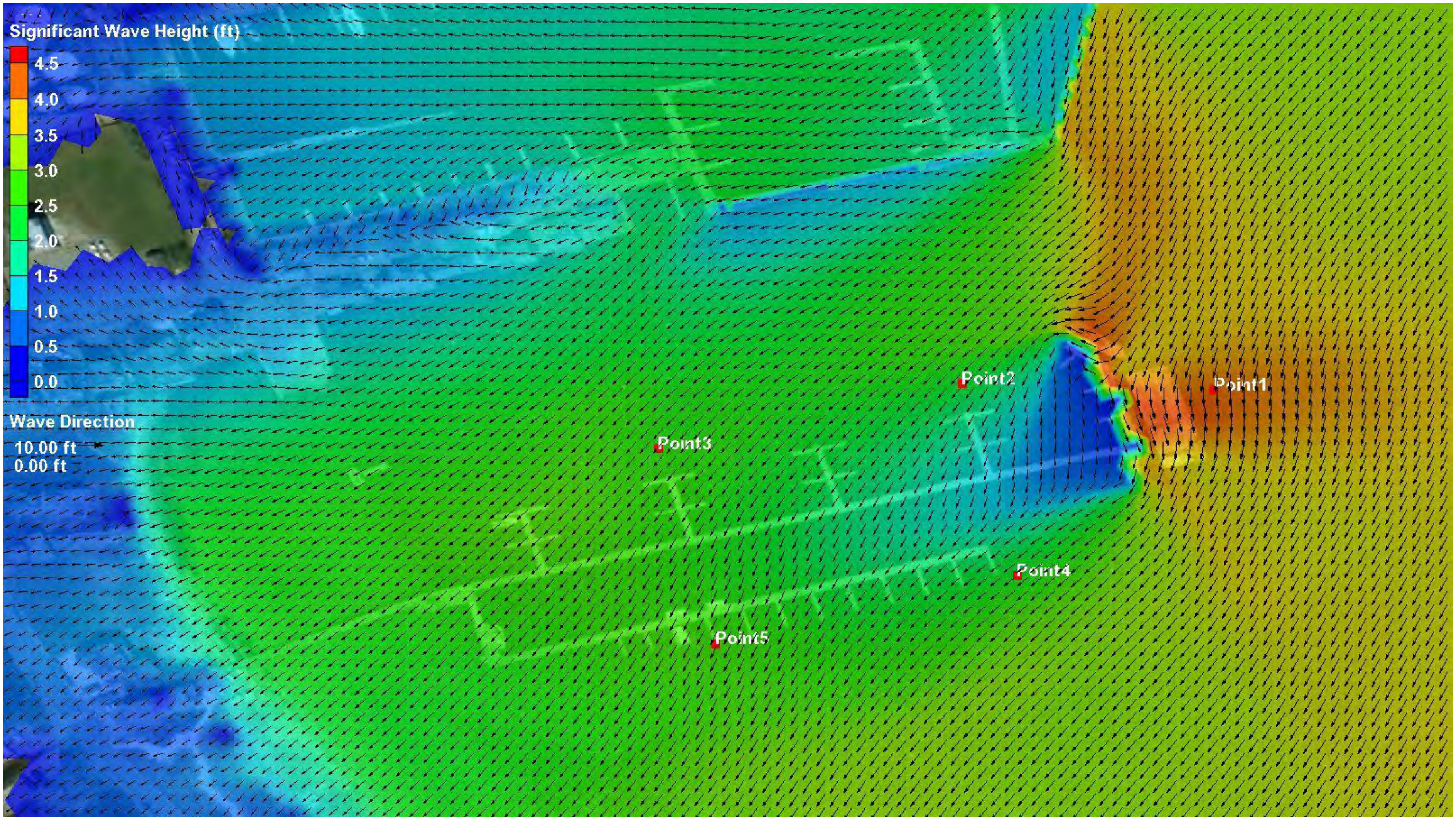

Figure 43: Significant Wave Height simulated by SWAN Wave Model for Run #6 – view 5

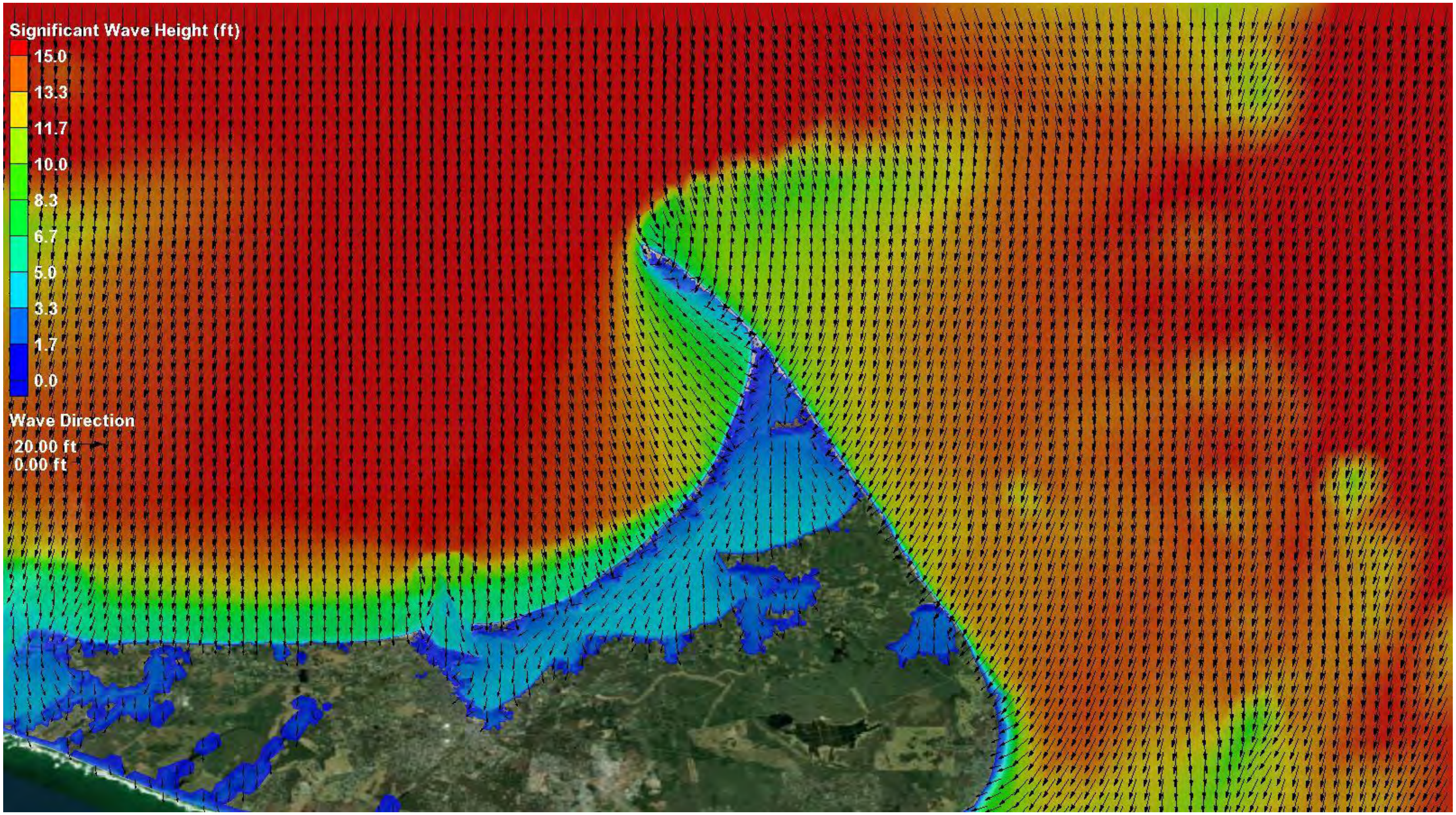

Figure 44: Significant Wave Height simulated by SWAN Wave Model for Run #7 – view 1

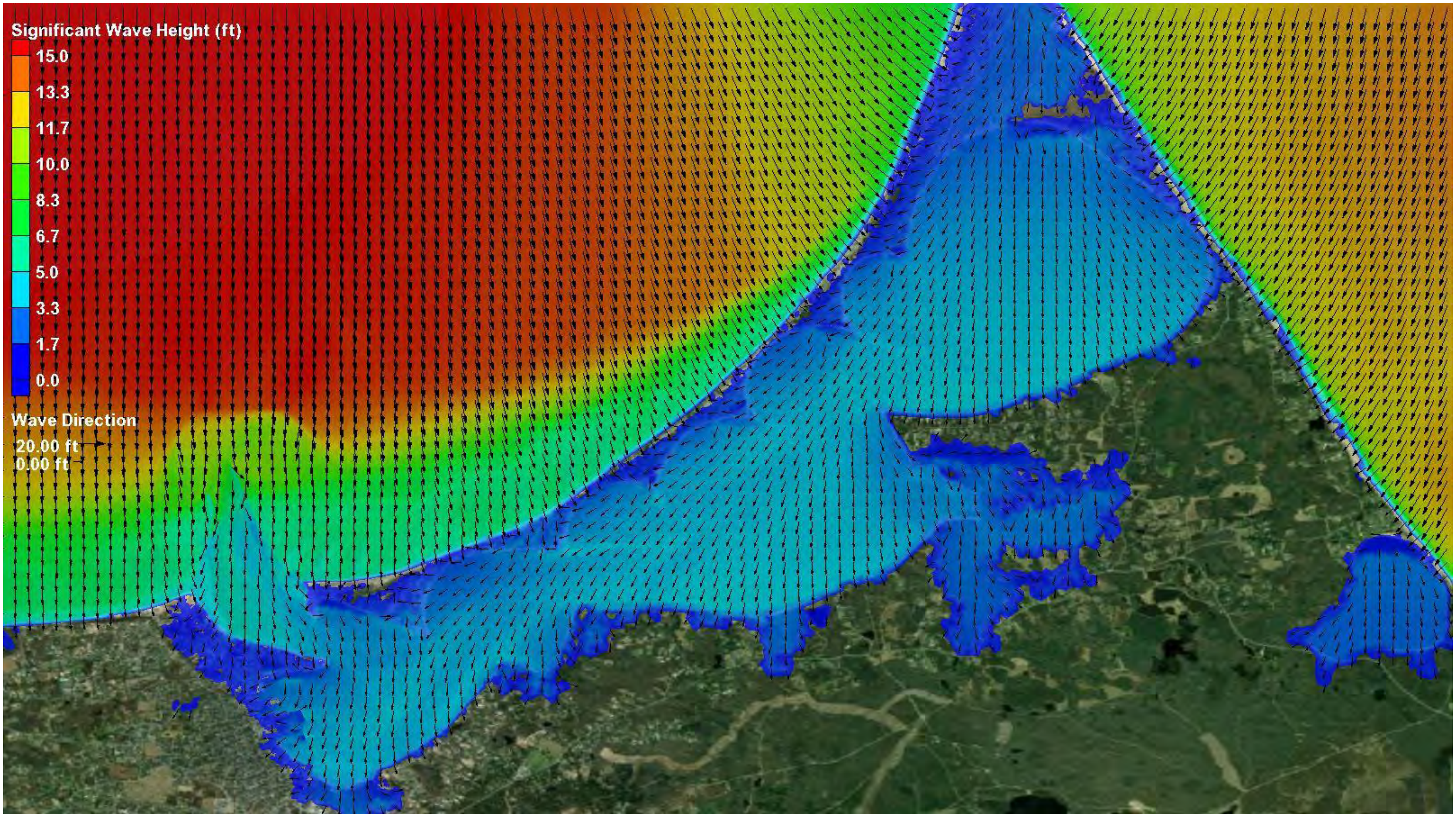

Figure 45: Significant Wave Height simulated by SWAN Wave Model for Run #7 – view 2

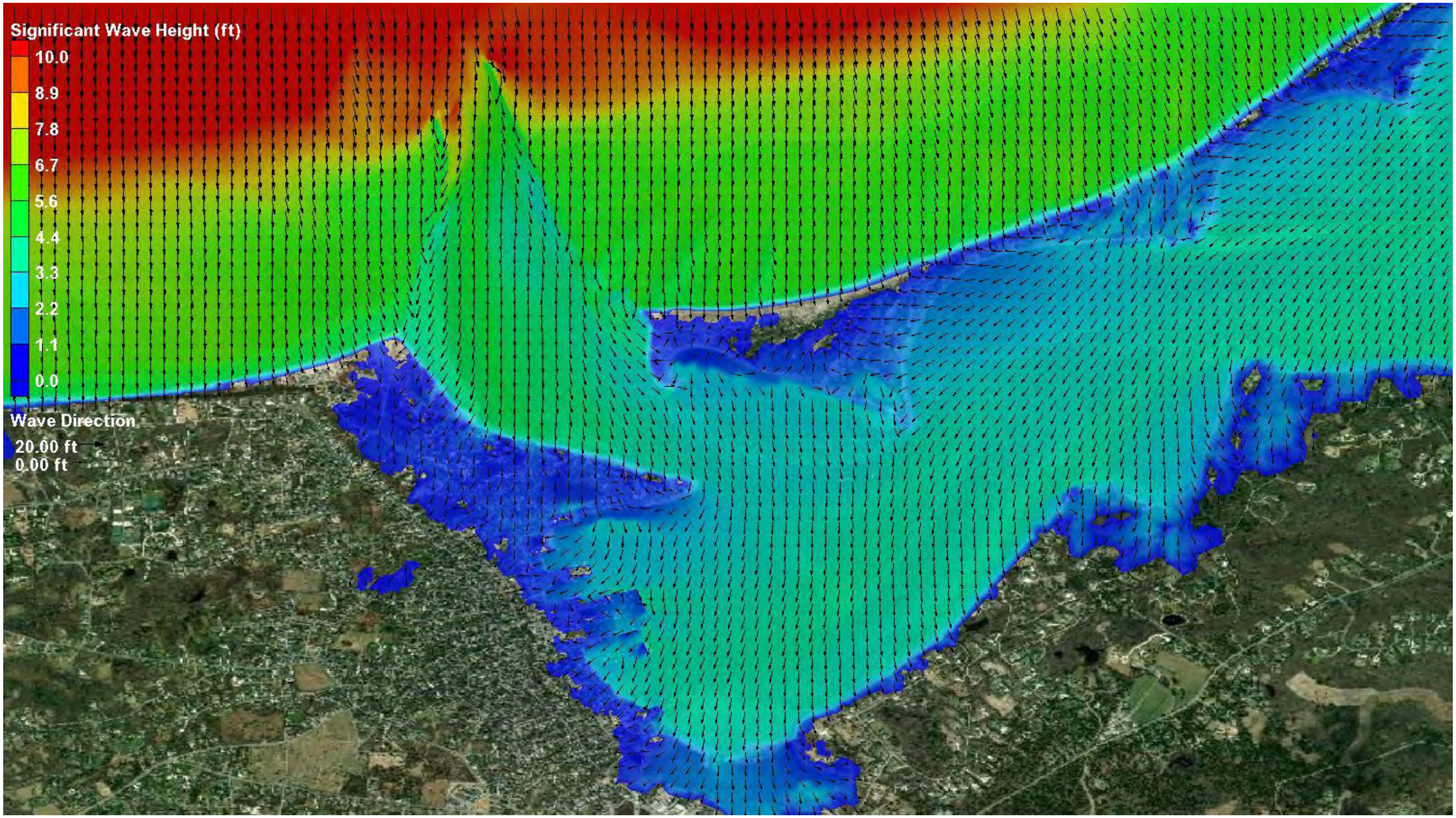

Figure 46: Significant Wave Height simulated by SWAN Wave Model for Run #7 – view 3

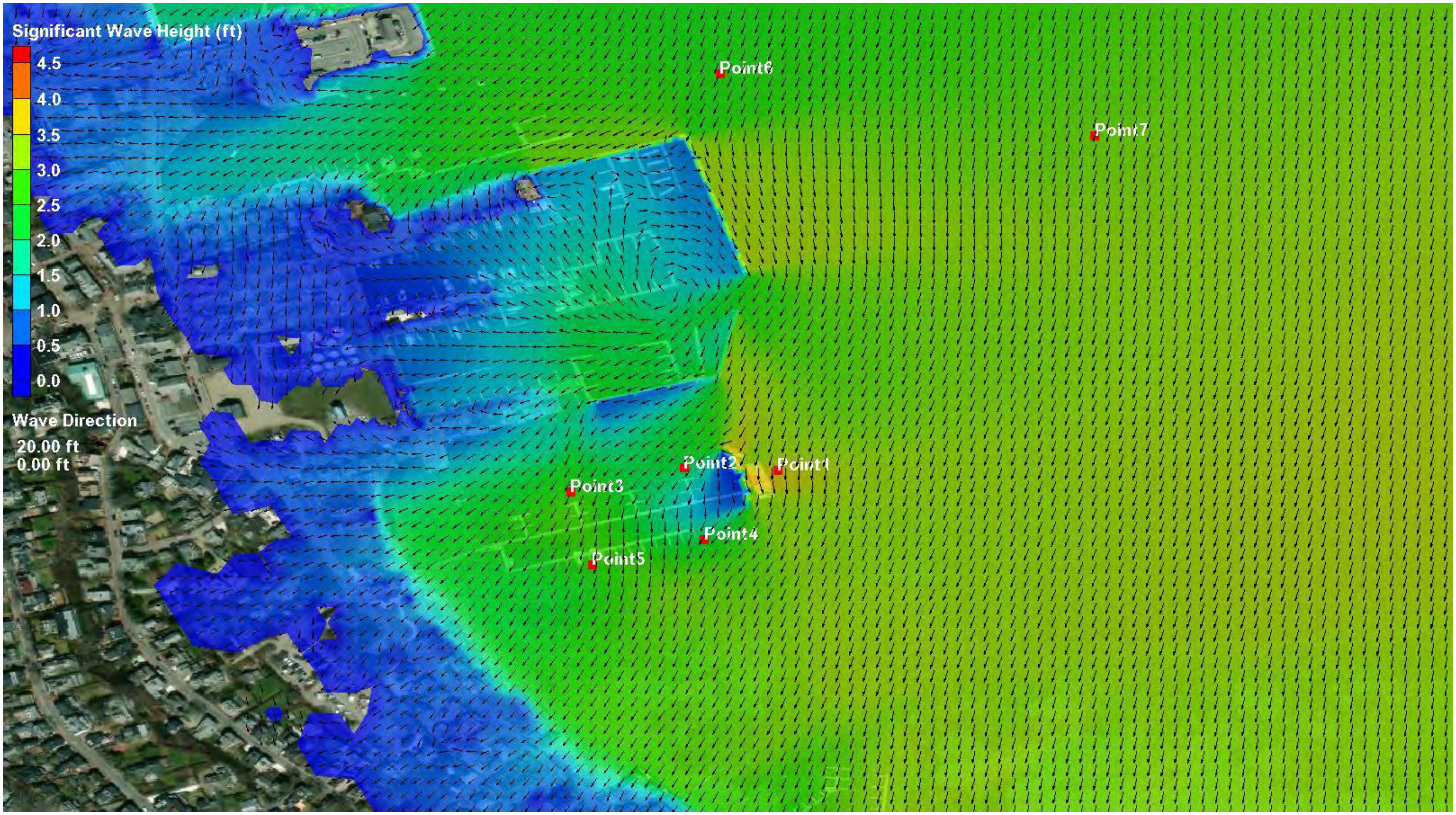

Figure 47: Significant Wave Height simulated by SWAN Wave Model for Run #7 – view 4

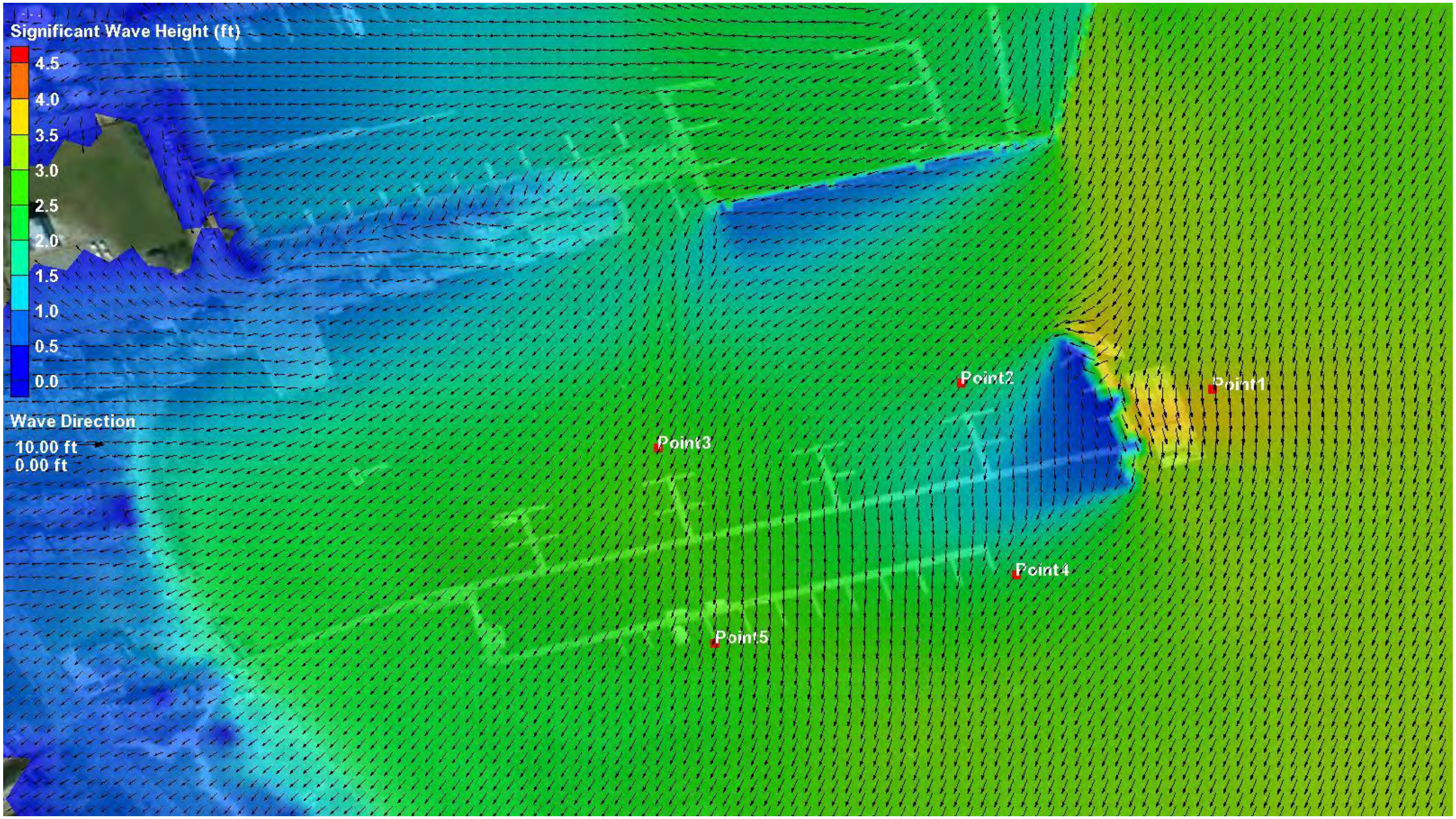

Figure 48: Significant Wave Height simulated by SWAN Wave Model for Run #7 – view 5

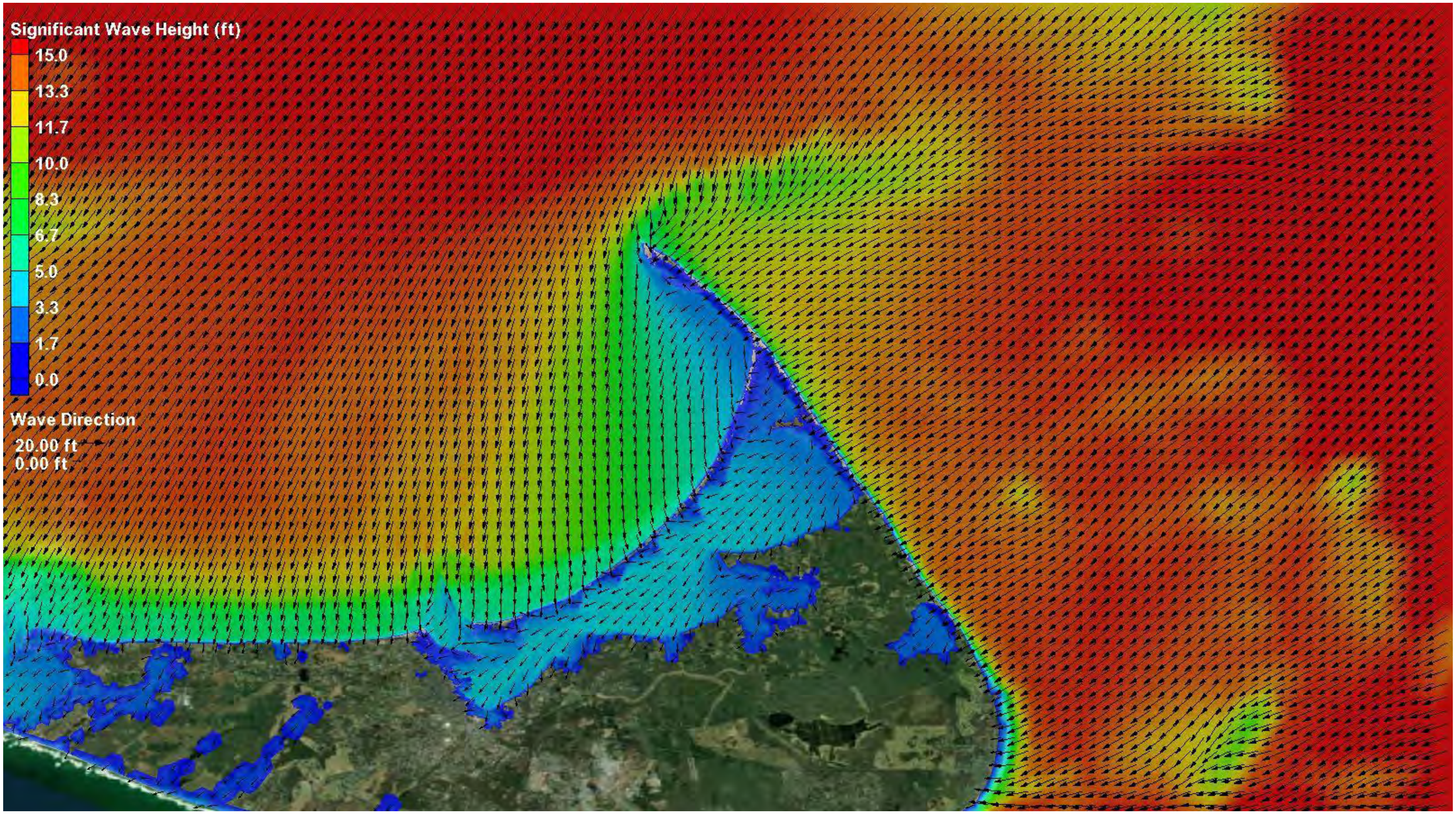

Figure 49: Significant Wave Height simulated by SWAN Wave Model for Run #8 – view 1

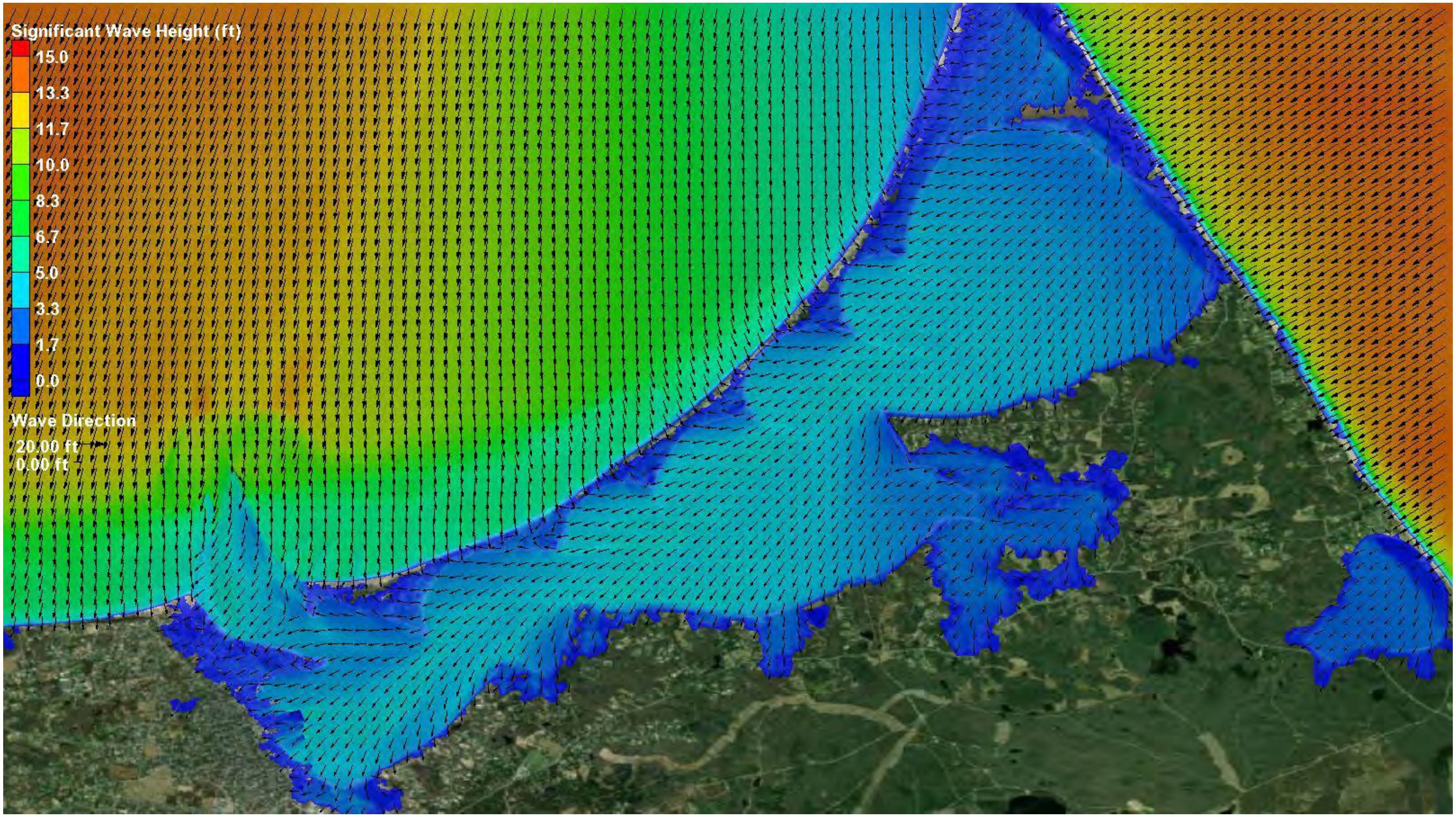

Figure 50: Significant Wave Height simulated by SWAN Wave Model for Run #8 – view 2

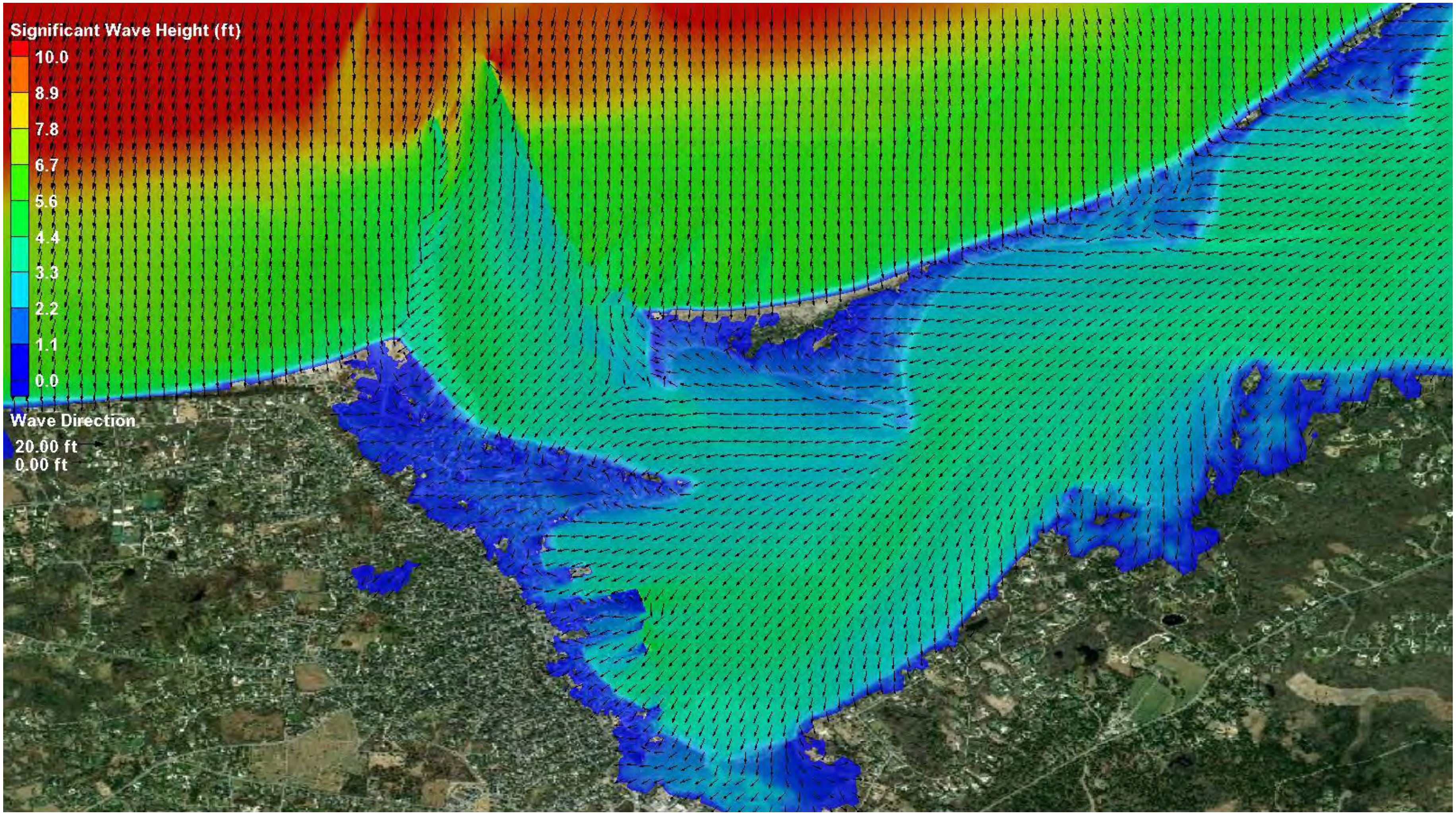

Figure 51: Significant Wave Height simulated by SWAN Wave Model for Run #8 – view 3

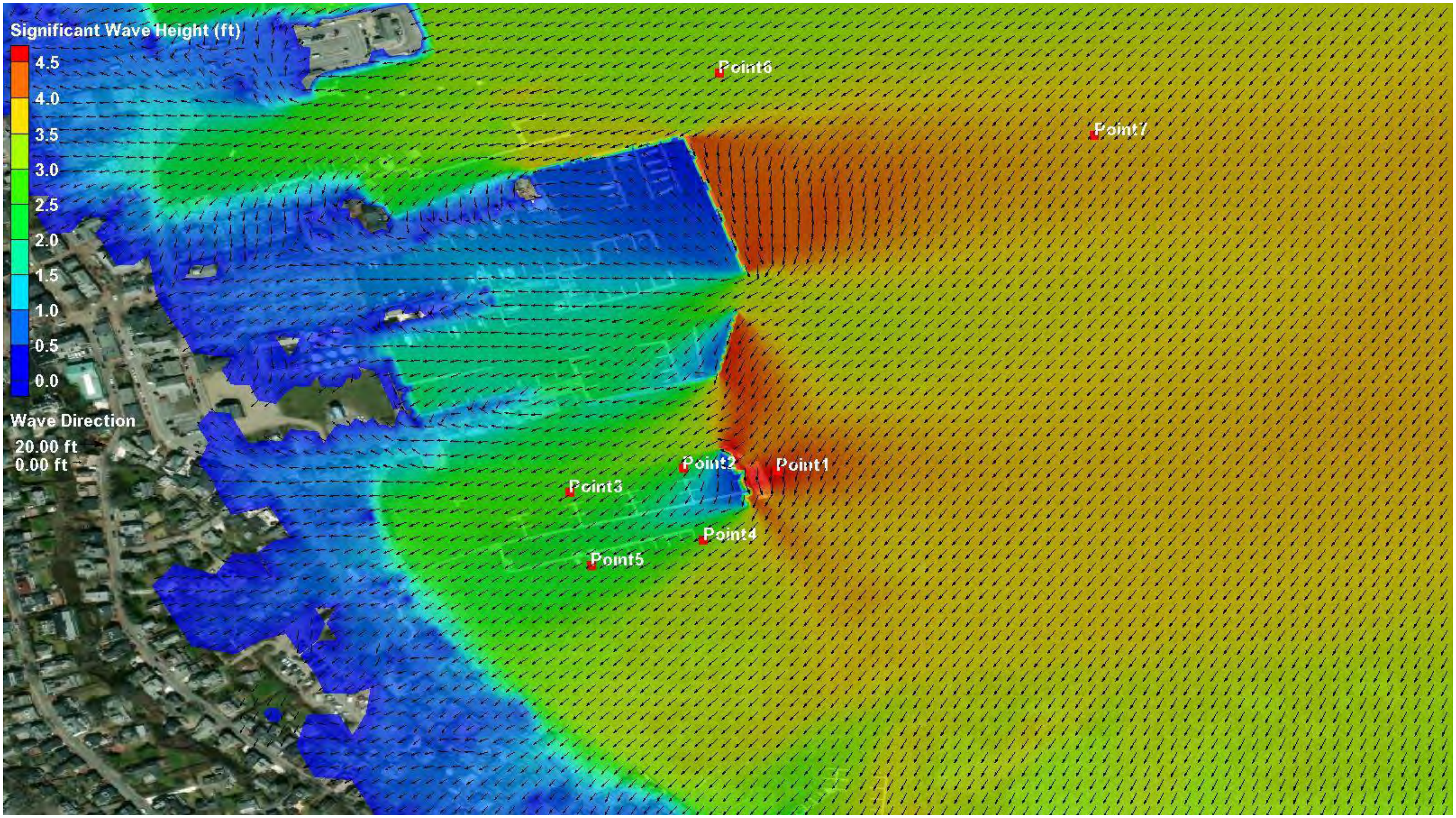

Figure 52: Significant Wave Height simulated by SWAN Wave Model for Run #8 – view 4

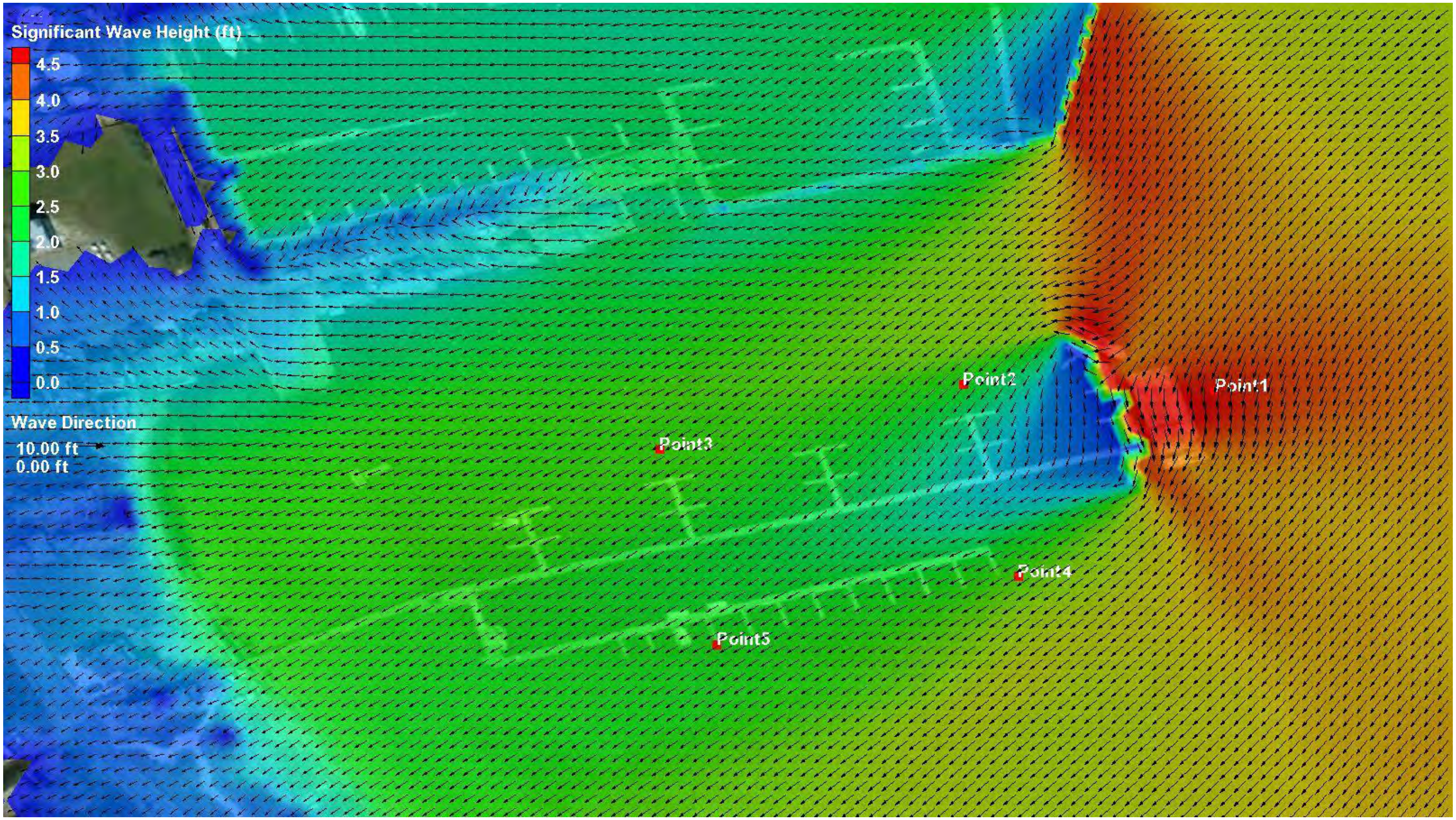

Figure 53: Significant Wave Height simulated by SWAN Wave Model for Run #8 – view 5

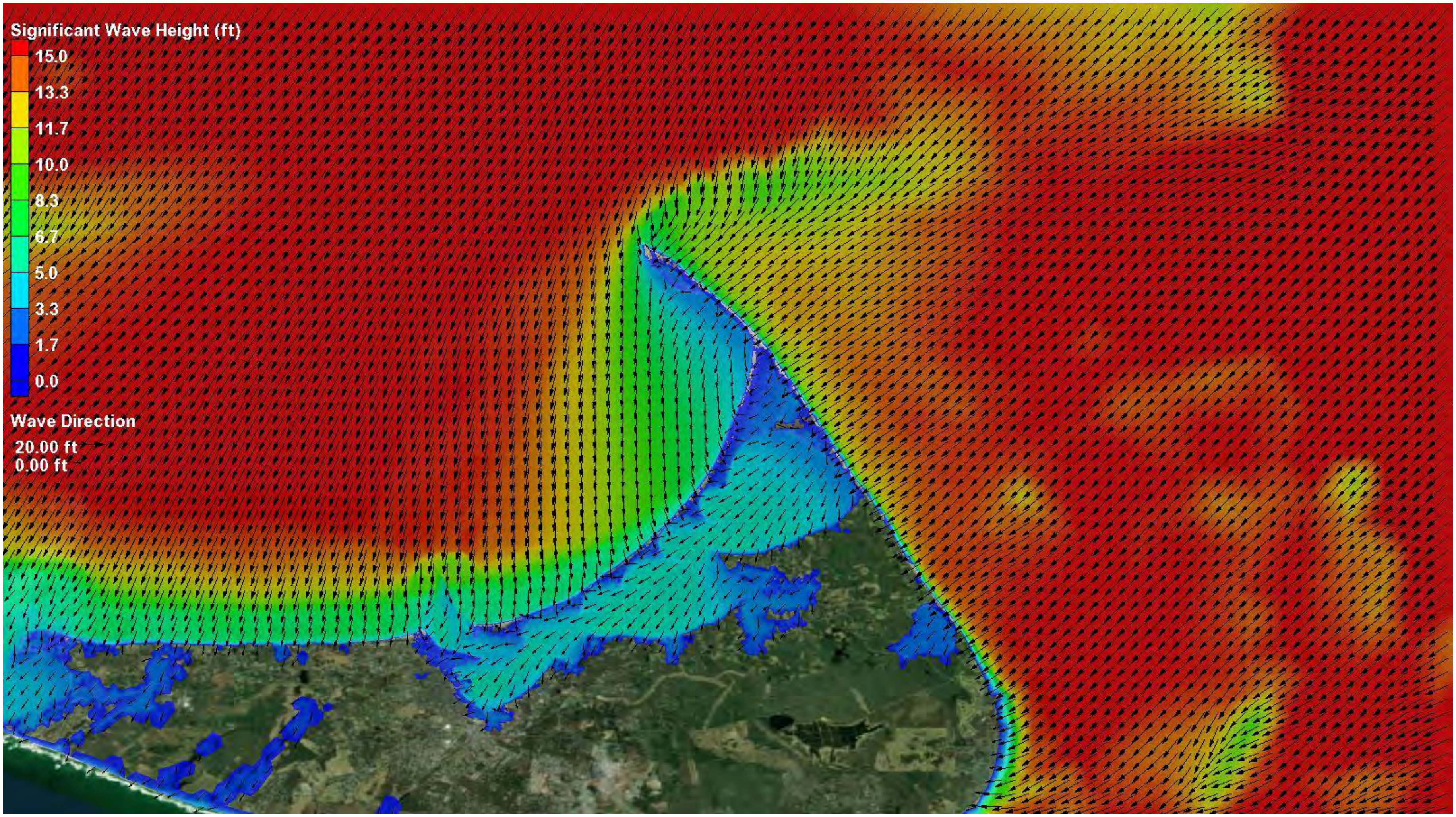

Figure 54: Significant Wave Height simulated by SWAN Wave Model for Run #13 – view 1

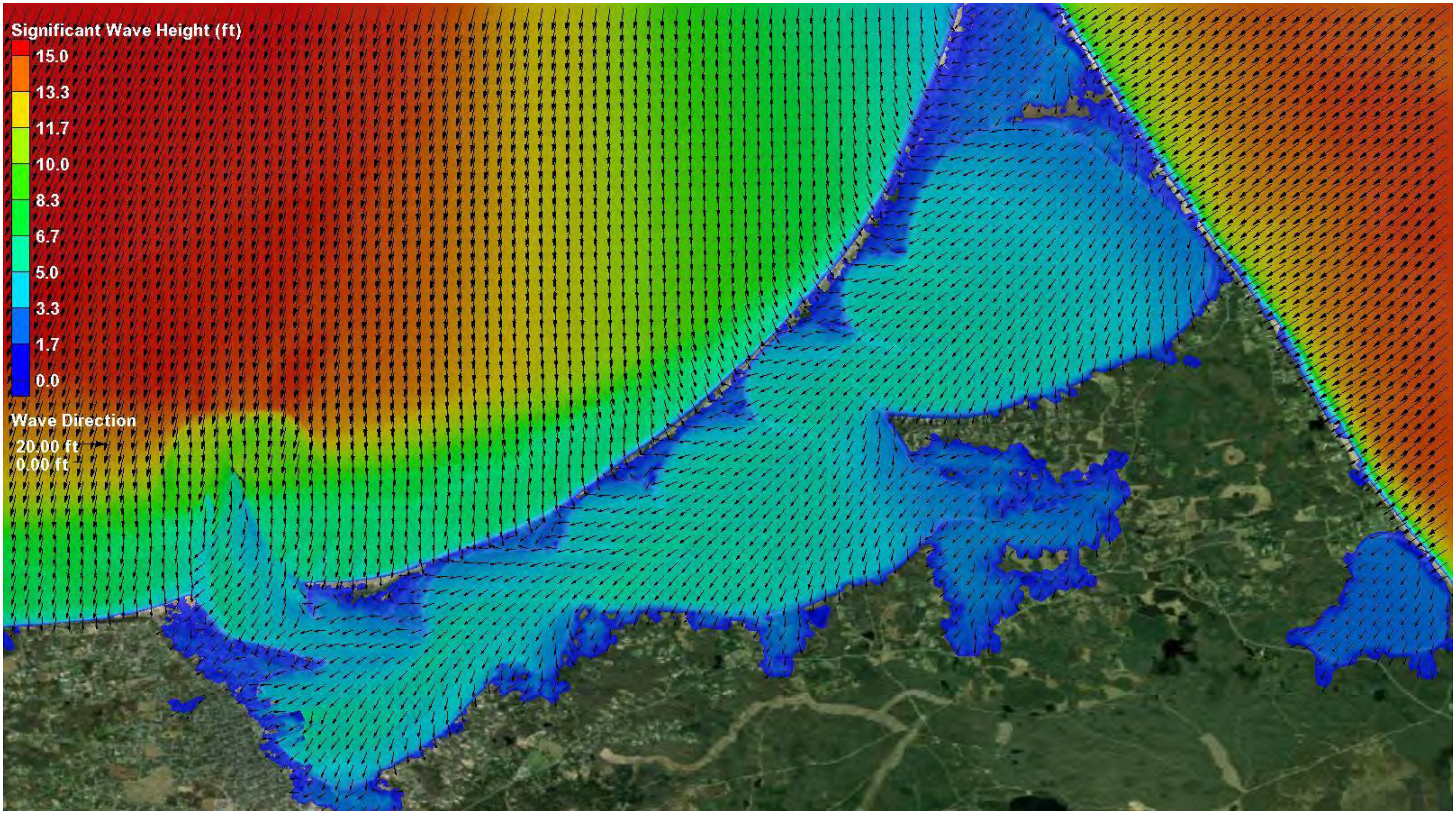

Figure 55: Significant Wave Height simulated by SWAN Wave Model for Run #13 – view 2

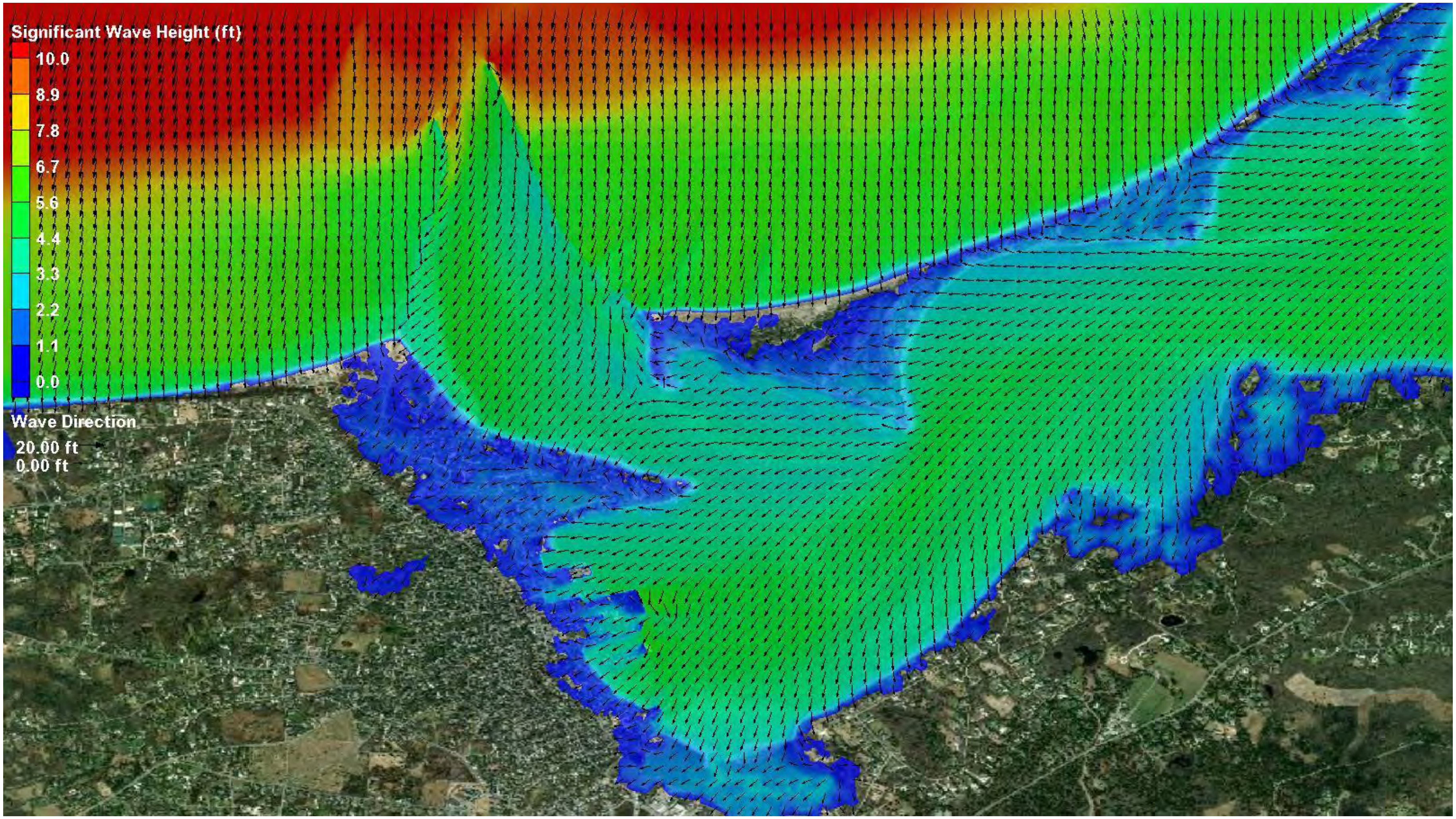

Figure 56: Significant Wave Height simulated by SWAN Wave Model for Run #13 – view 3

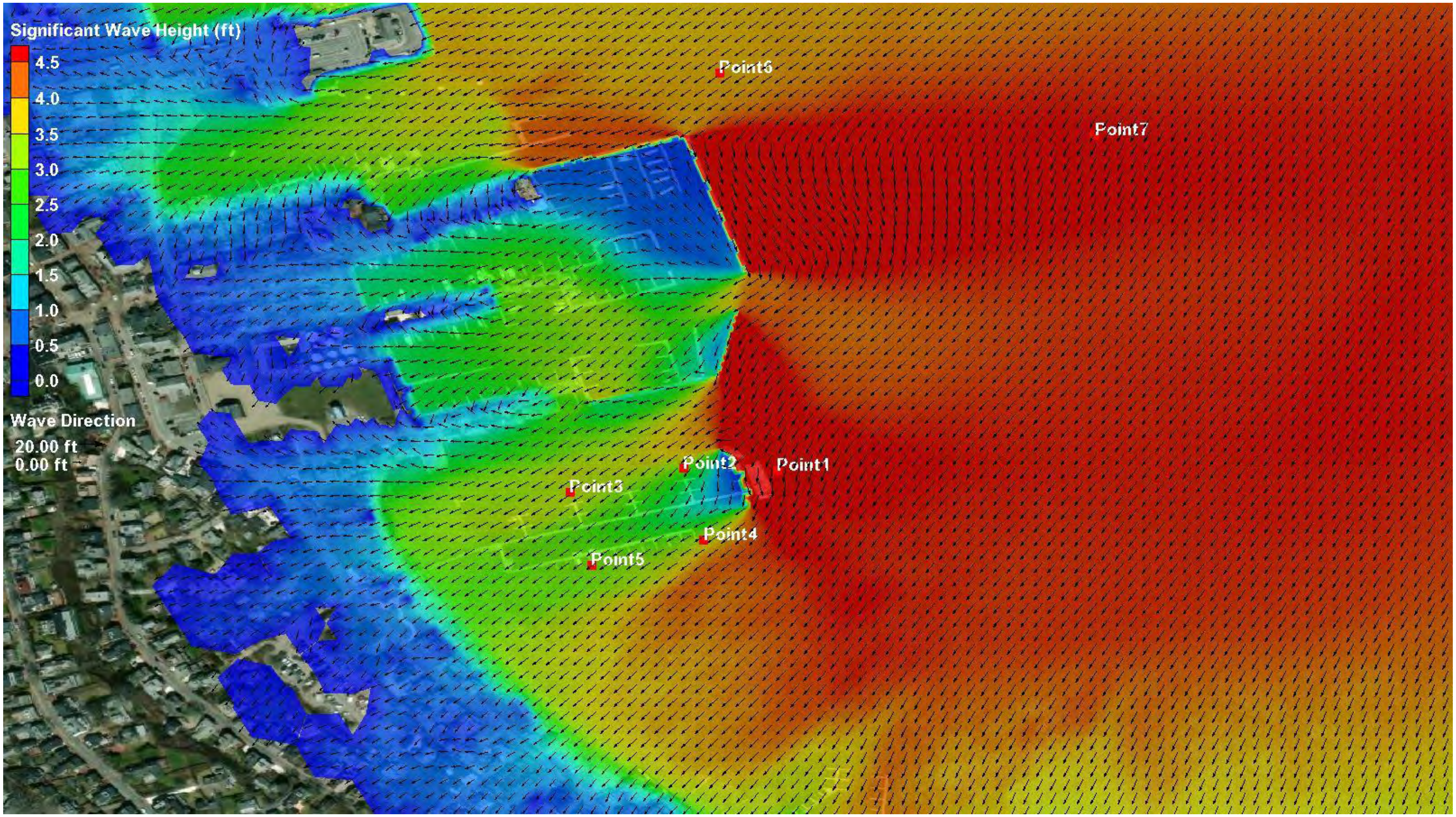

Figure 57: Significant Wave Height simulated by SWAN Wave Model for Run #13 – view 4

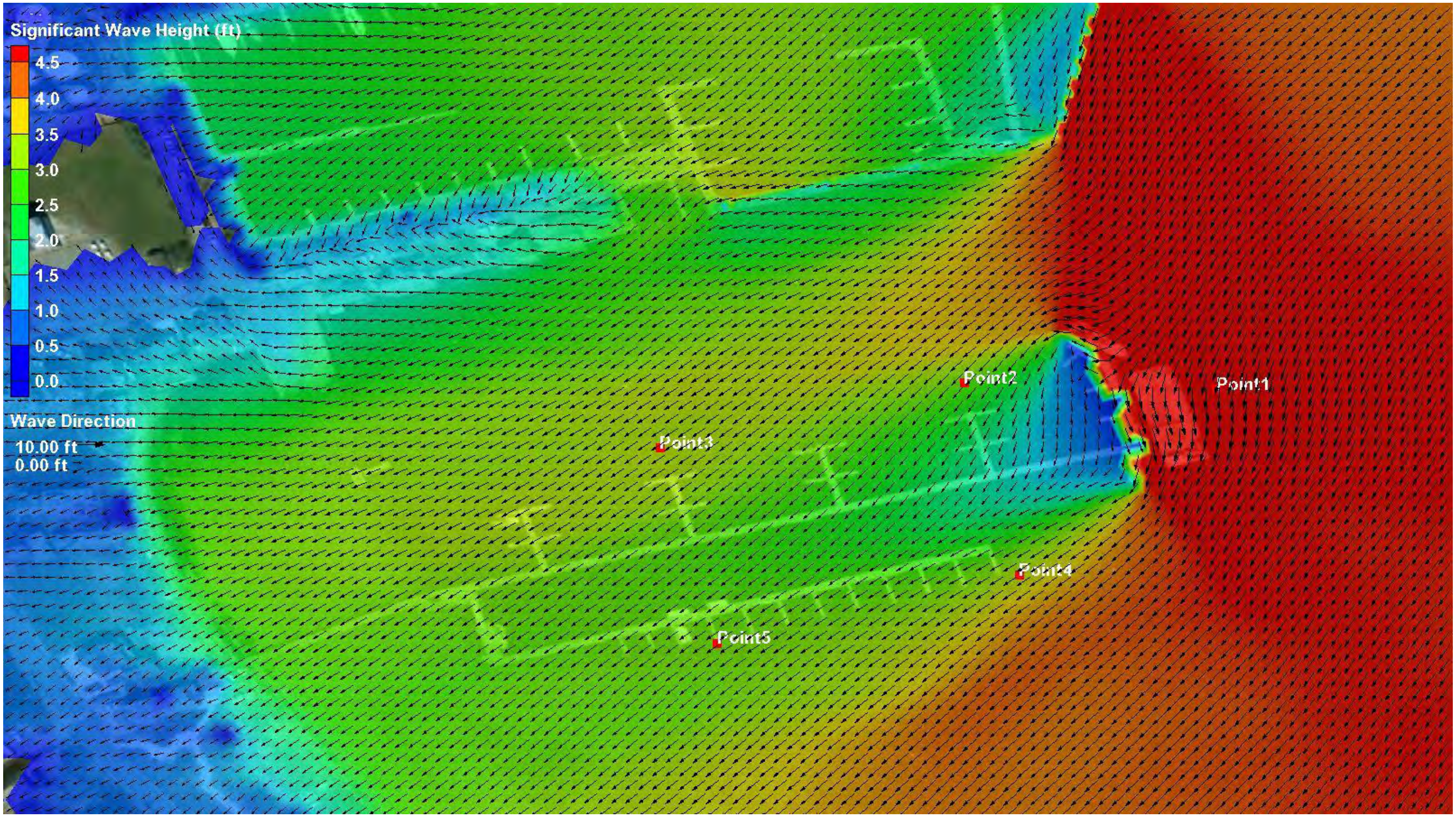

Figure 58: Significant Wave Height simulated by SWAN Wave Model for Run #13 – view 5

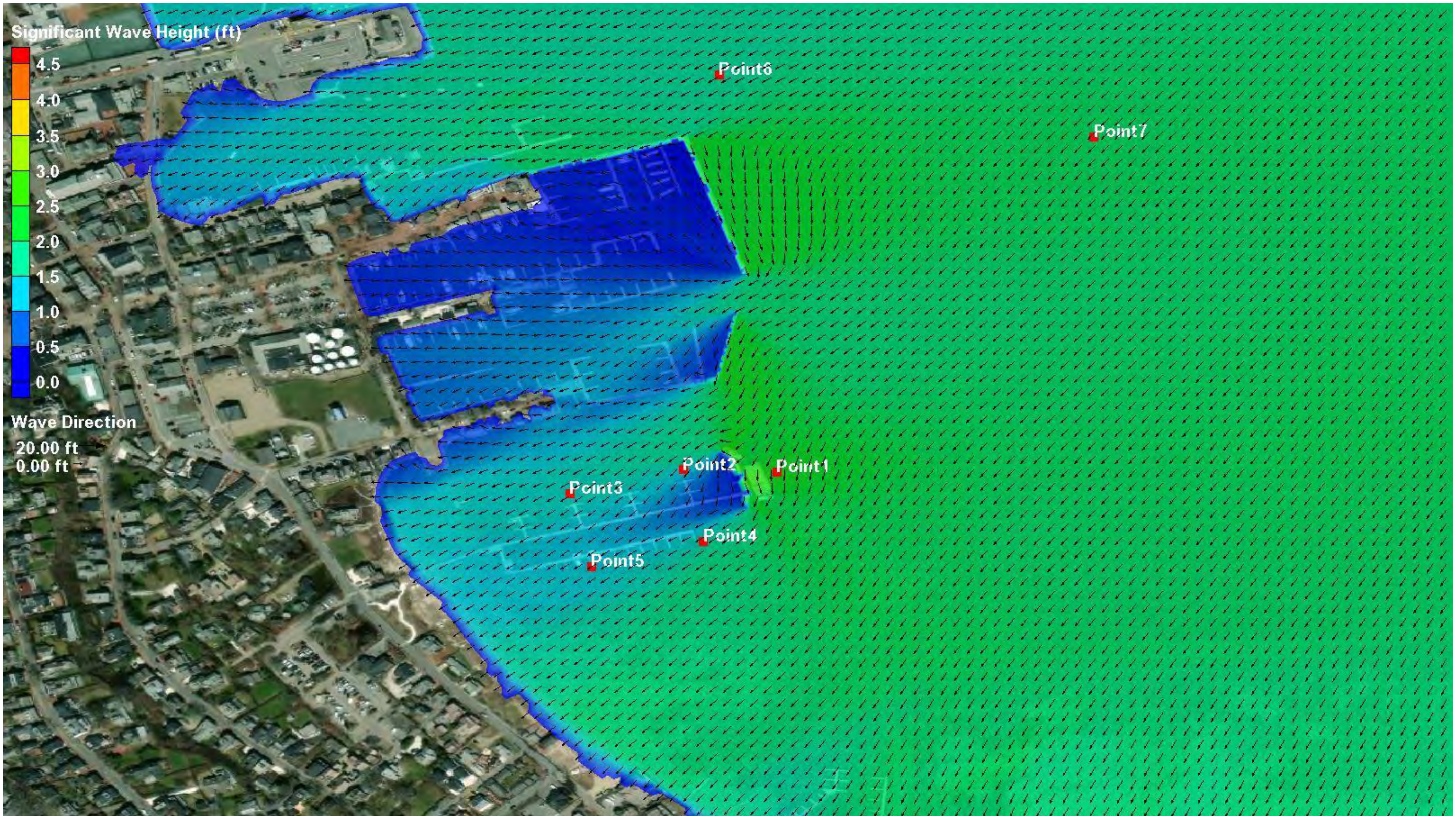

Figure 59: Significant Wave Height simulated by SWAN Wave Model for Run #14 – view 4

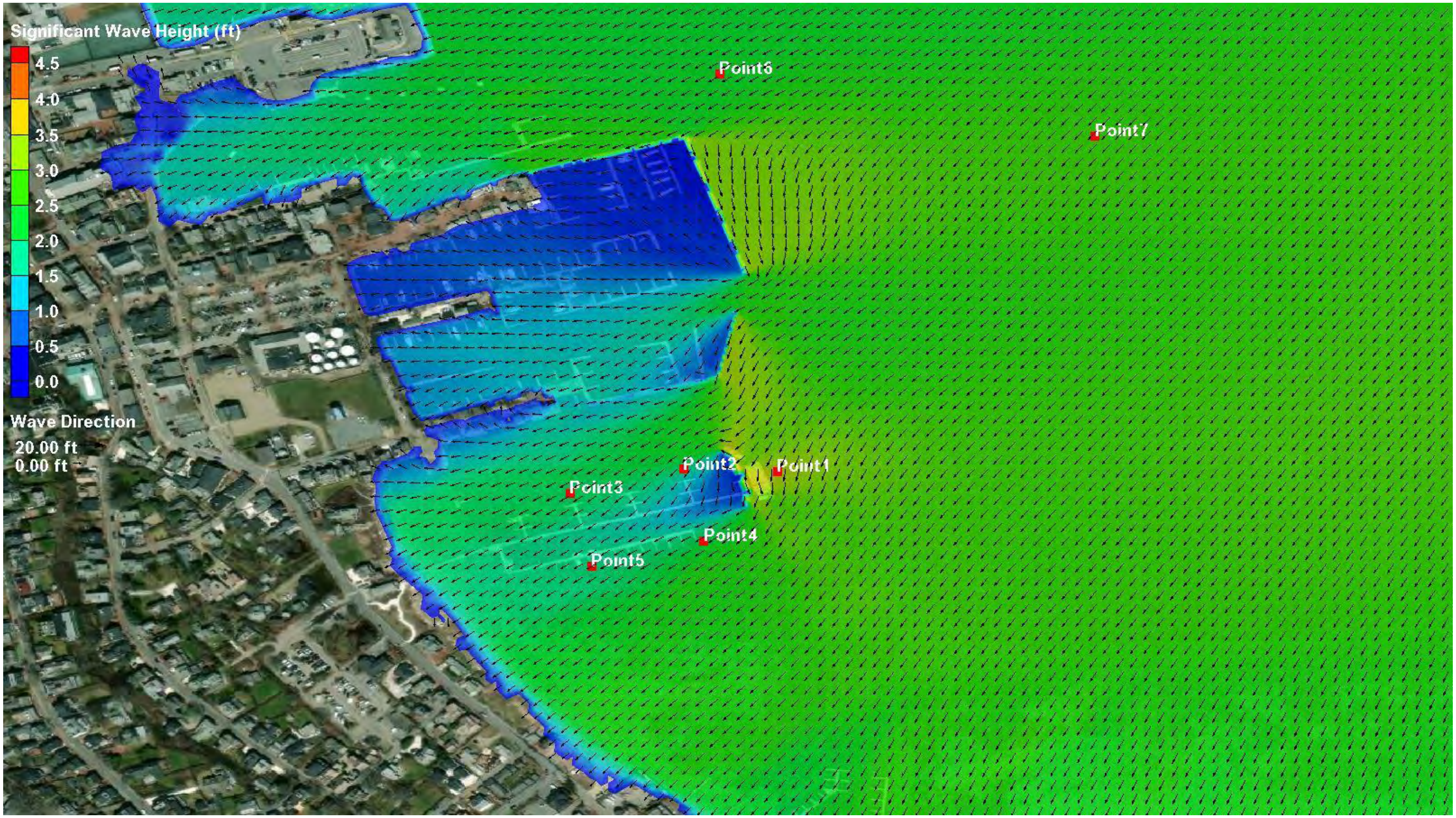

Figure 60: Significant Wave Height simulated by SWAN Wave Model for Run #15 – view 4

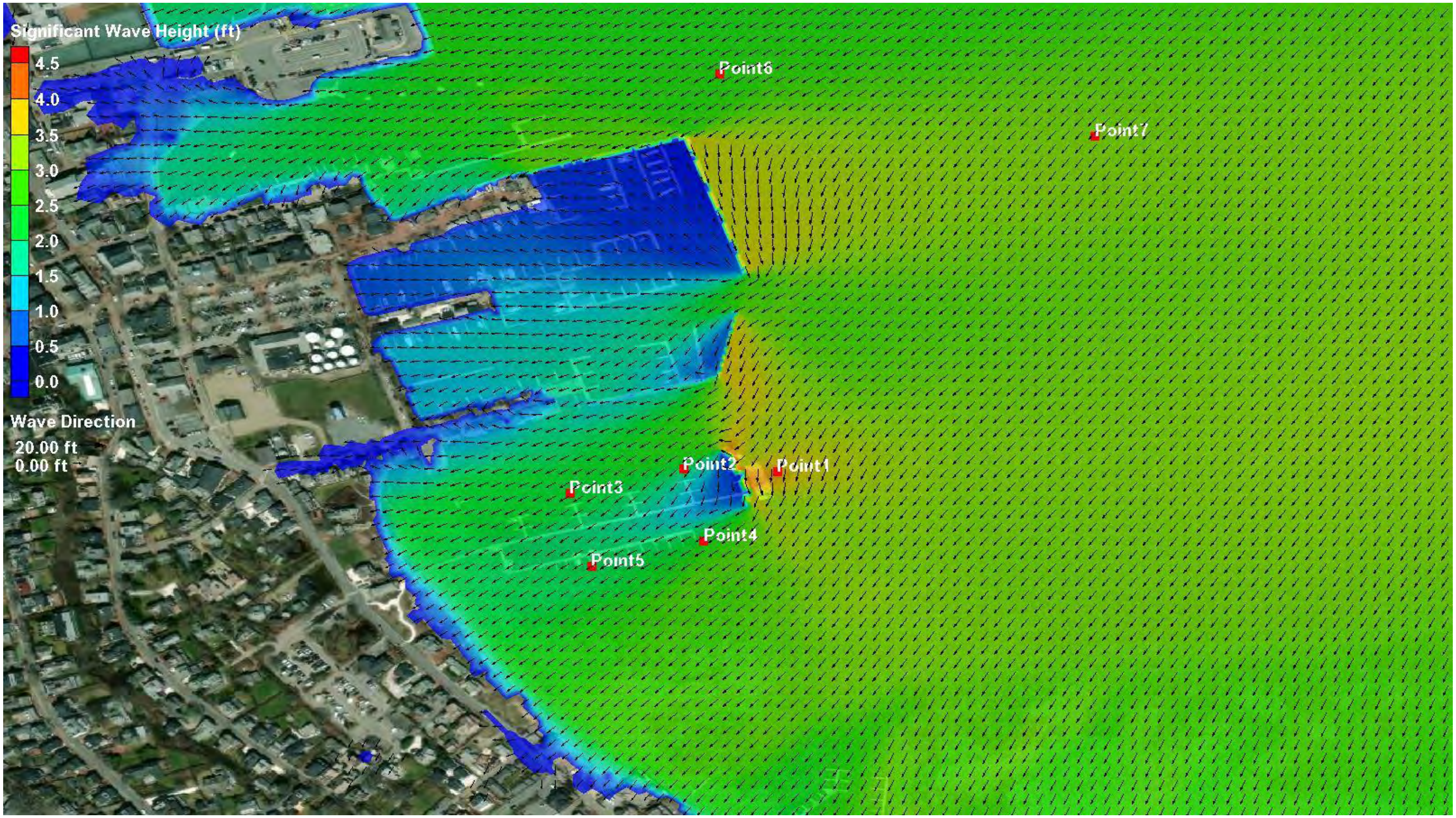

Figure 61: Significant Wave Height simulated by SWAN Wave Model for Run #16 – view 4

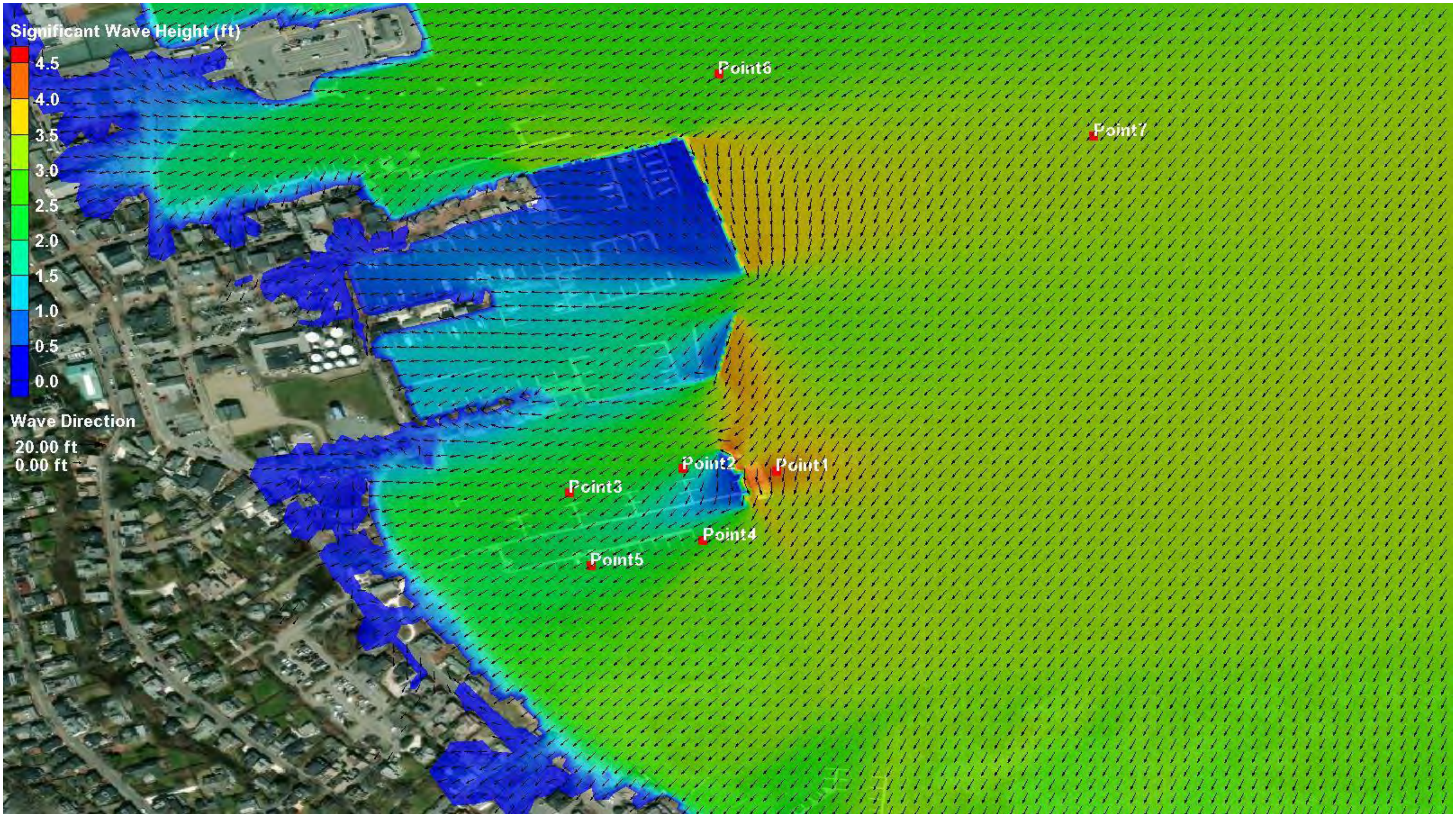

Figure 62: Significant Wave Height simulated by SWAN Wave Model for Run #17 – view 4

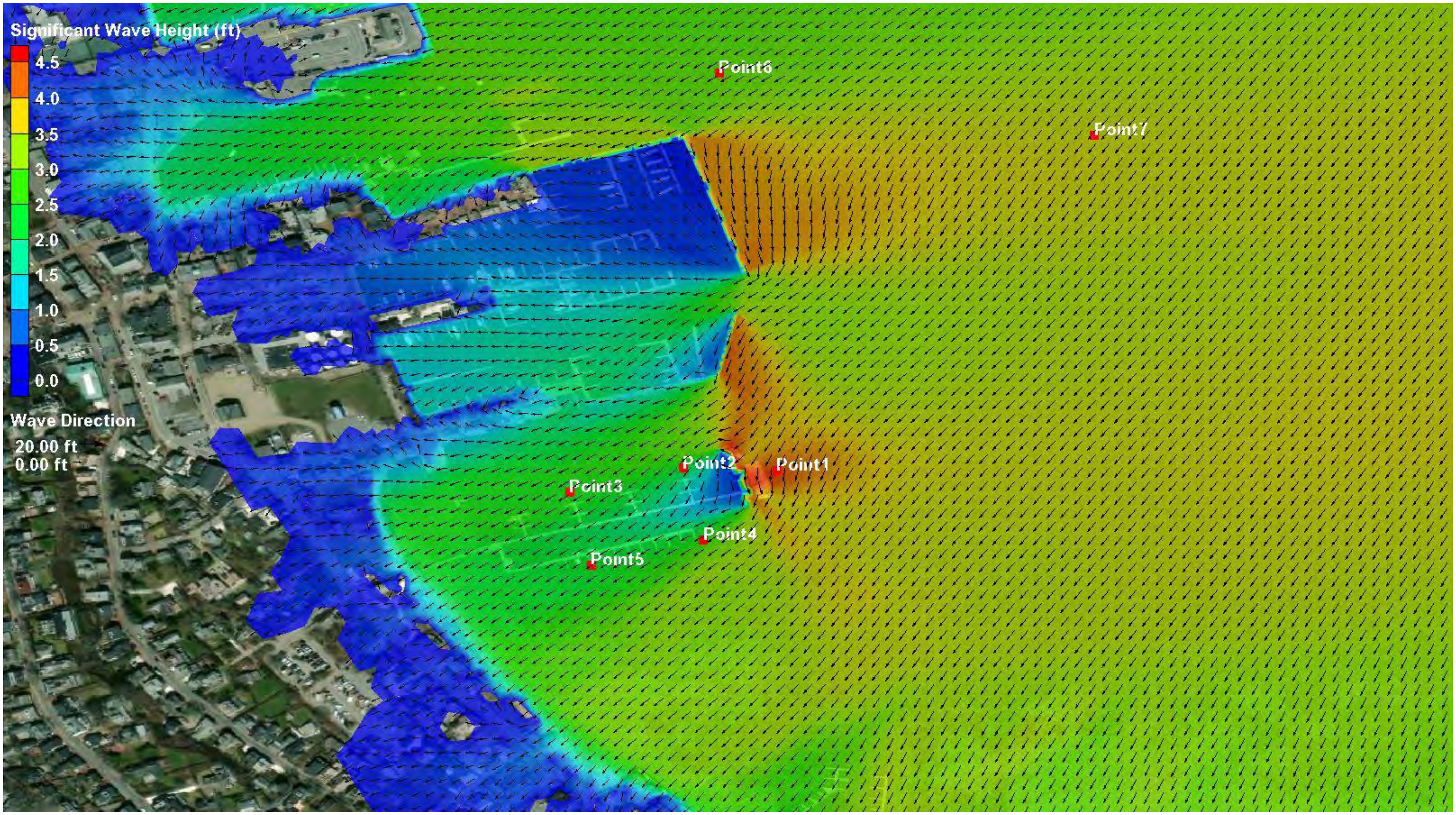

Figure 63: Significant Wave Height simulated by SWAN Wave Model for Run #18 – view 4

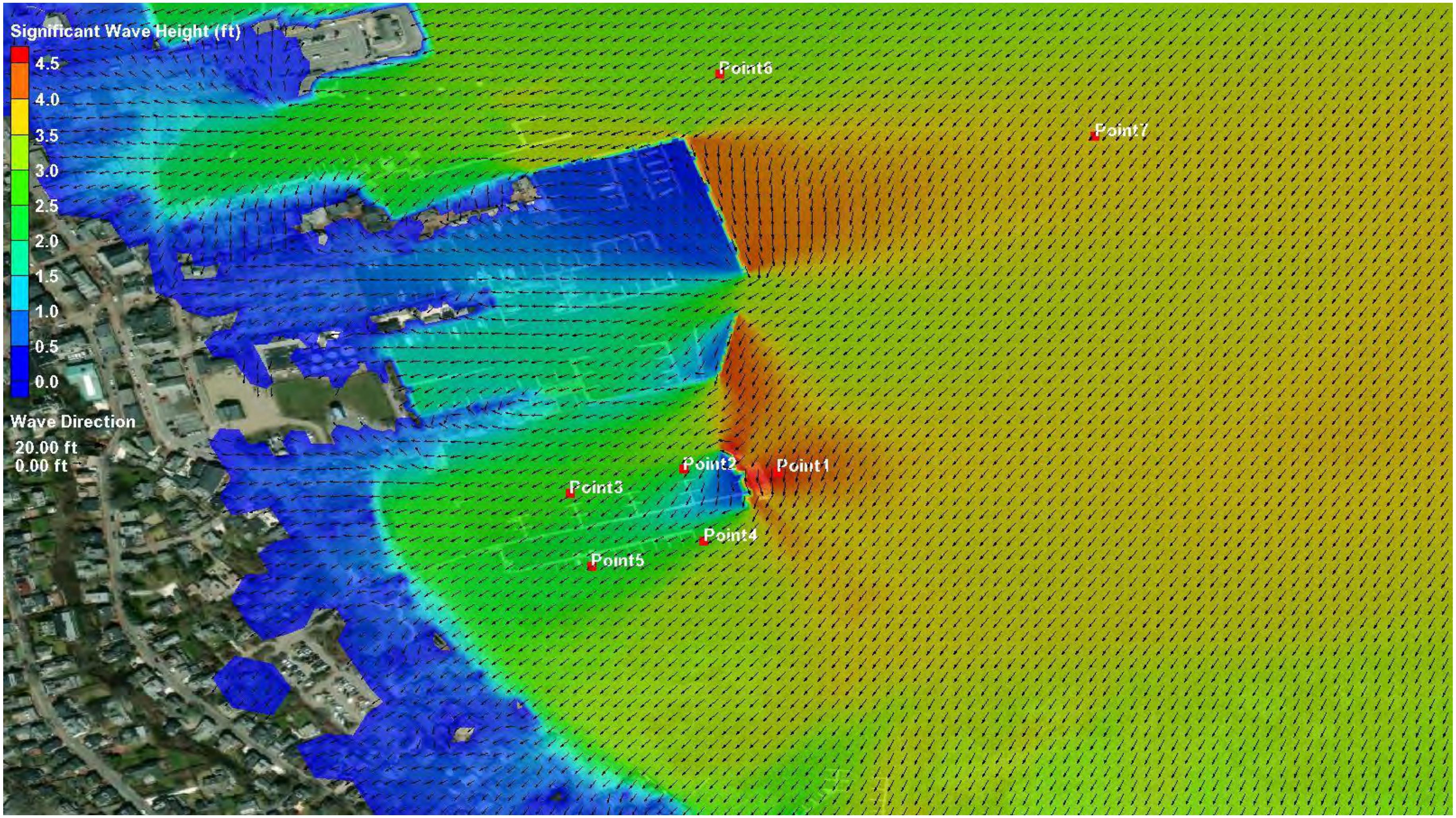

Figure 64: Significant Wave Height simulated by SWAN Wave Model for Run #19 – view 4

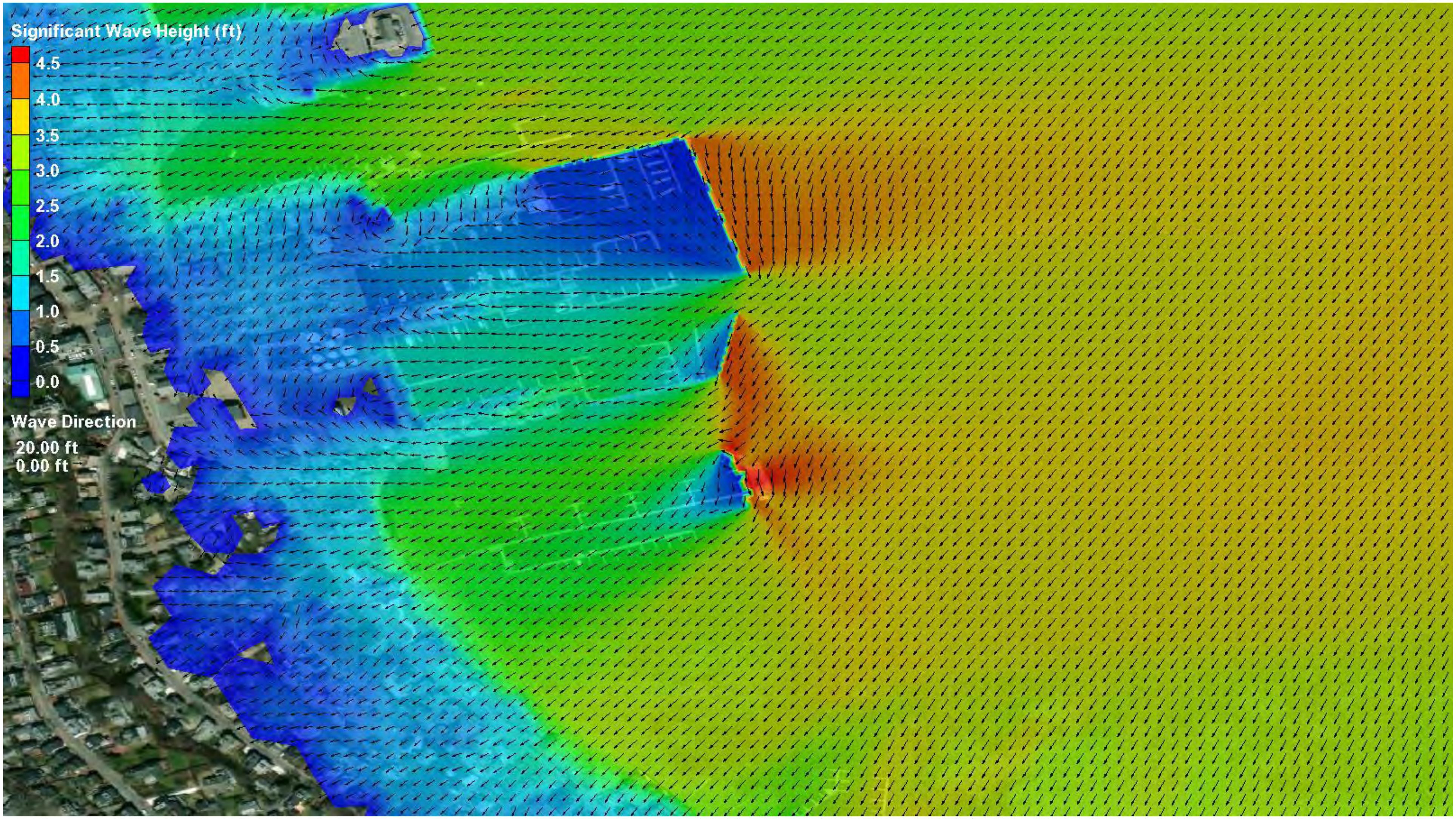

Figure 65: Significant Wave Height simulated by SWAN Wave Model for Run #10A – view 4

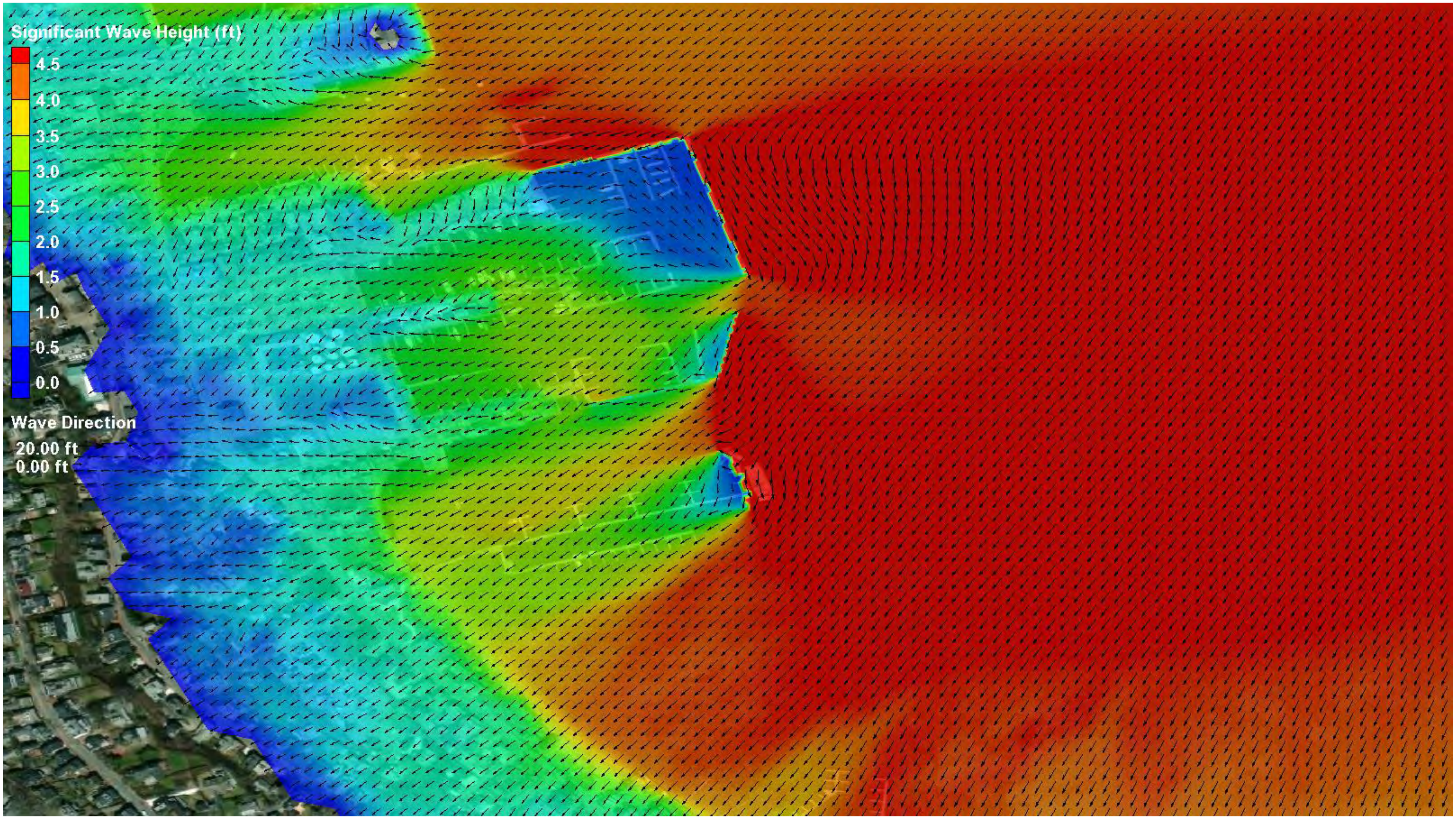

Figure 66: Significant Wave Height simulated by SWAN Wave Model for Run #13A – view 4

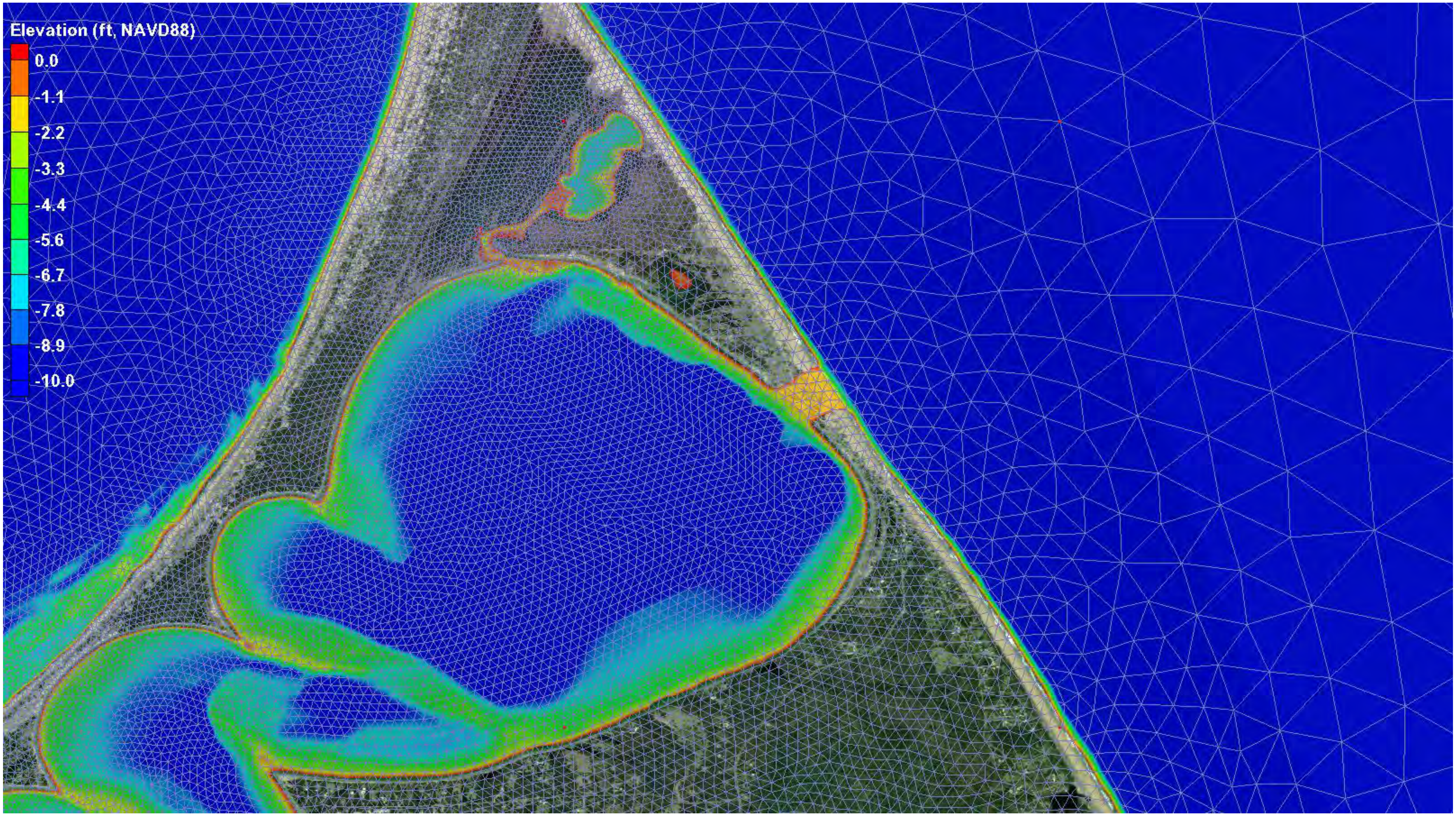

Figure 67: Hypothetical breach to depth of MLW (i.e., -1.84 ft, NAVD88) at barrier beach with breach width of approximately 800 feet for Run #13B

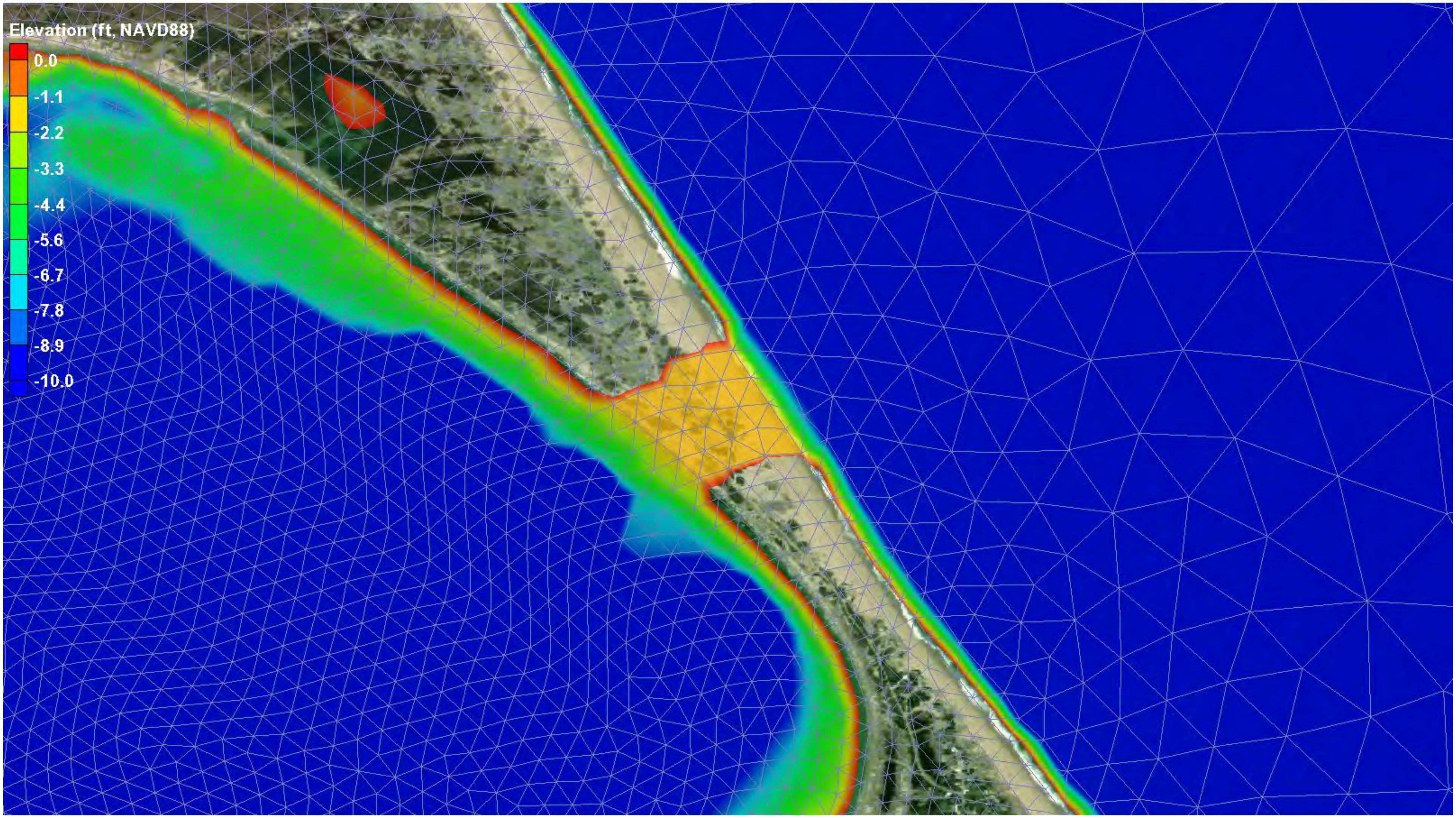

Figure 68: Hypothetical breach to depth of MLW (i.e., -1.84 ft, NAVD88) at barrier beach with breach width of approximately 800 feet for Run #13B

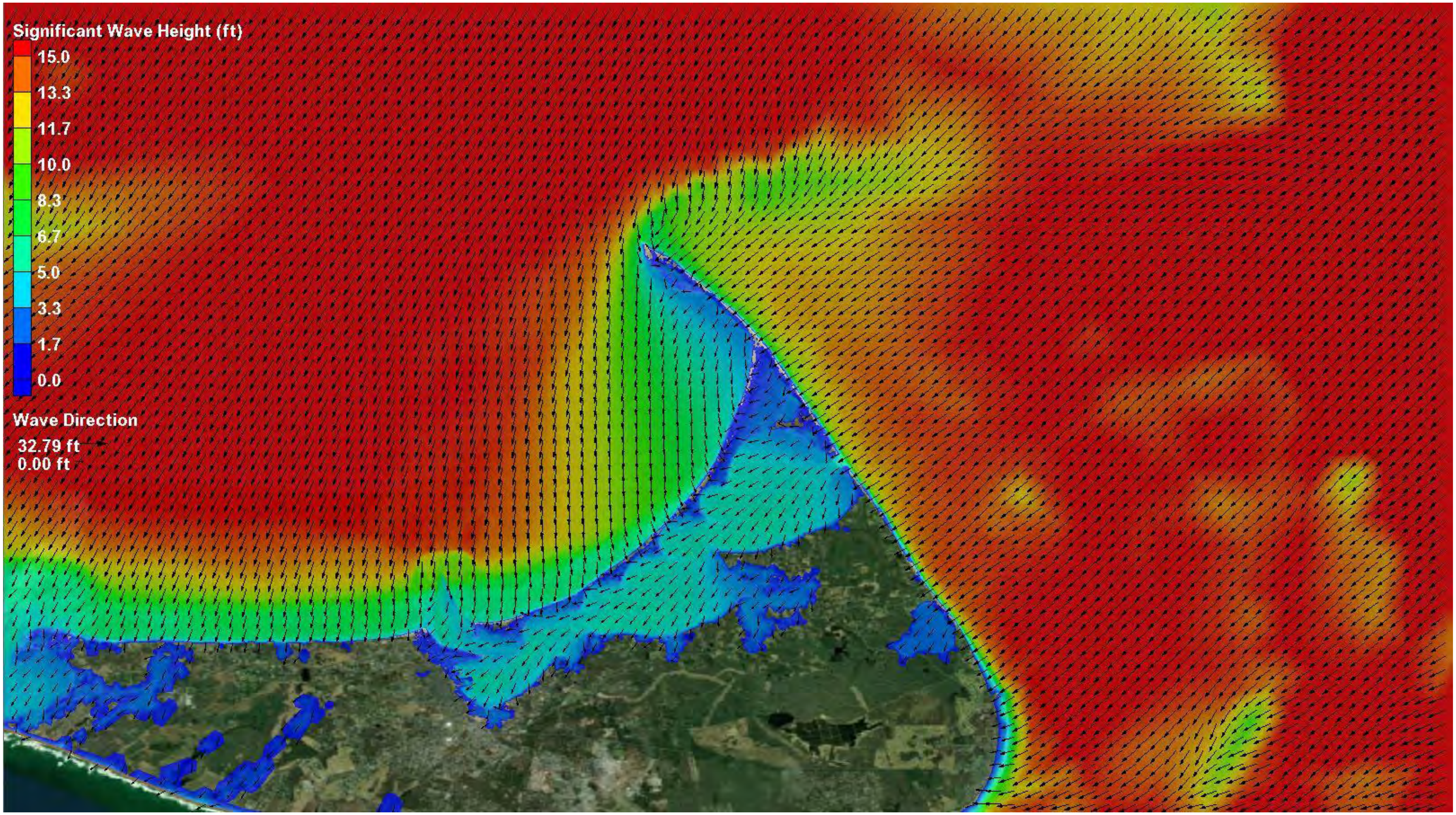

Figure 69: Significant Wave Height simulated by SWAN Wave Model for Run #13B – view 1

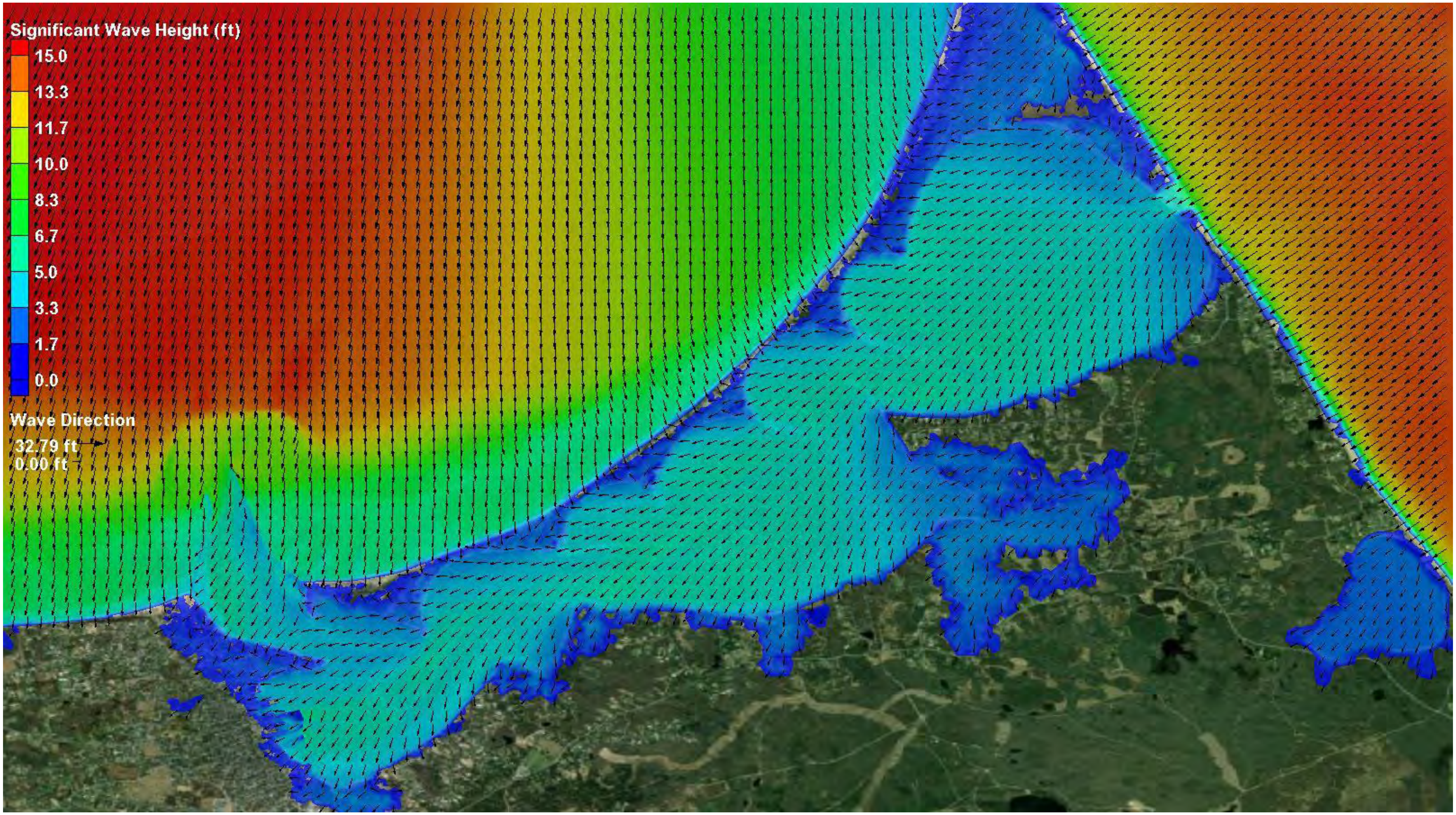

Figure 70: Significant Wave Height simulated by SWAN Wave Model for Run #13B – view 2

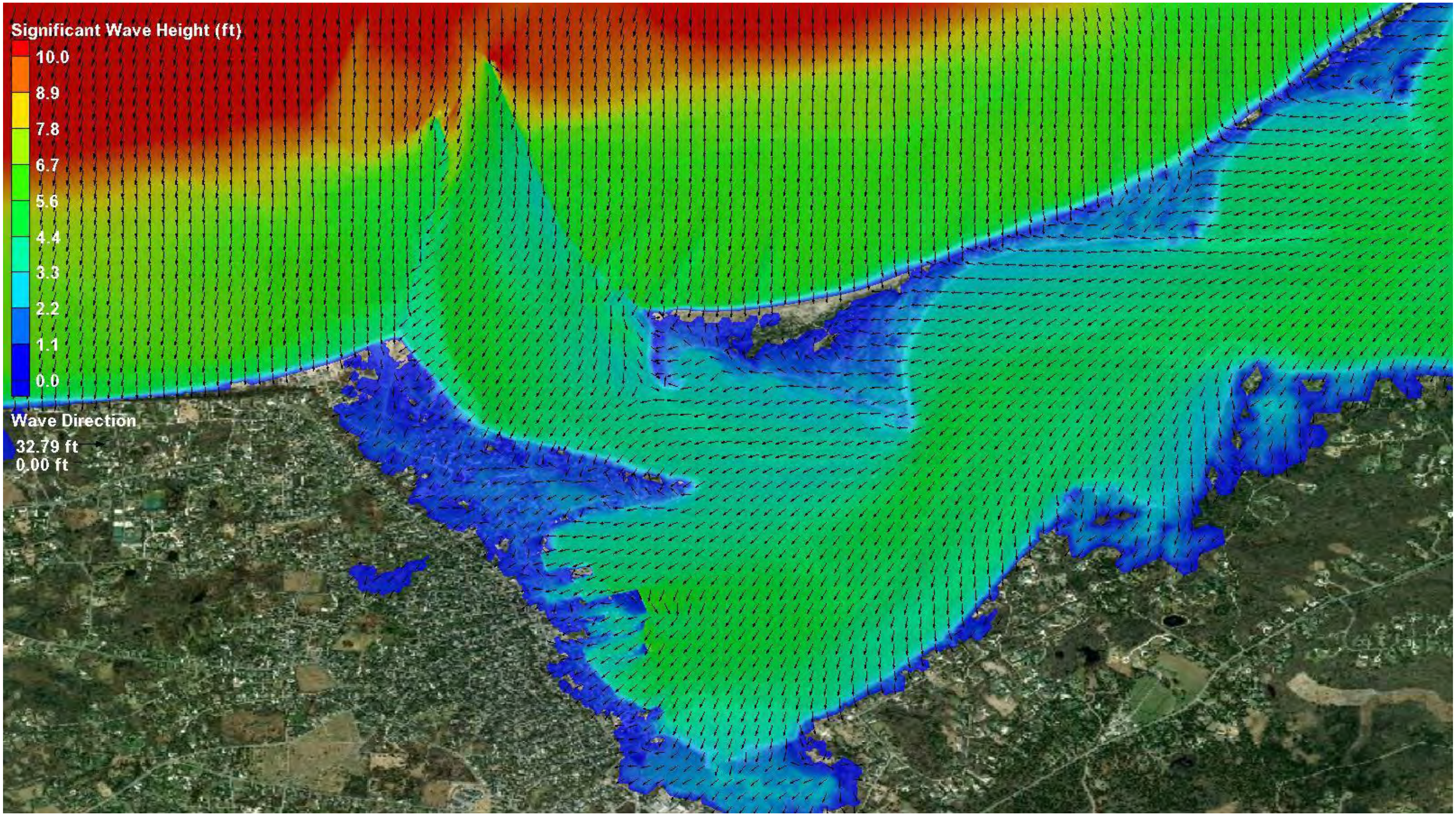

Figure 71: Significant Wave Height simulated by SWAN Wave Model for Run #13B – view 3

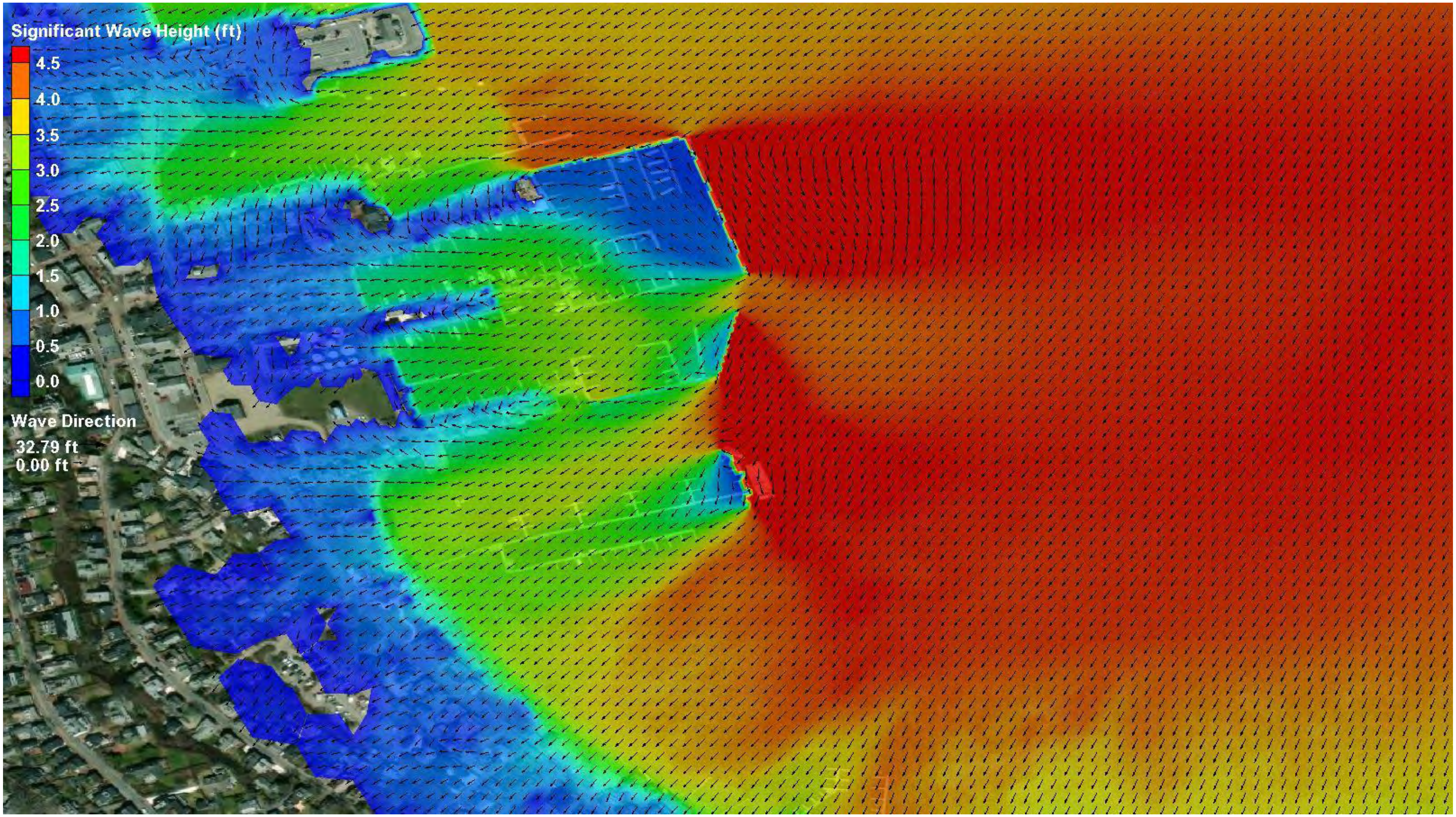

Figure 72: Significant Wave Height simulated by SWAN Wave Model for Run #13B – view 4

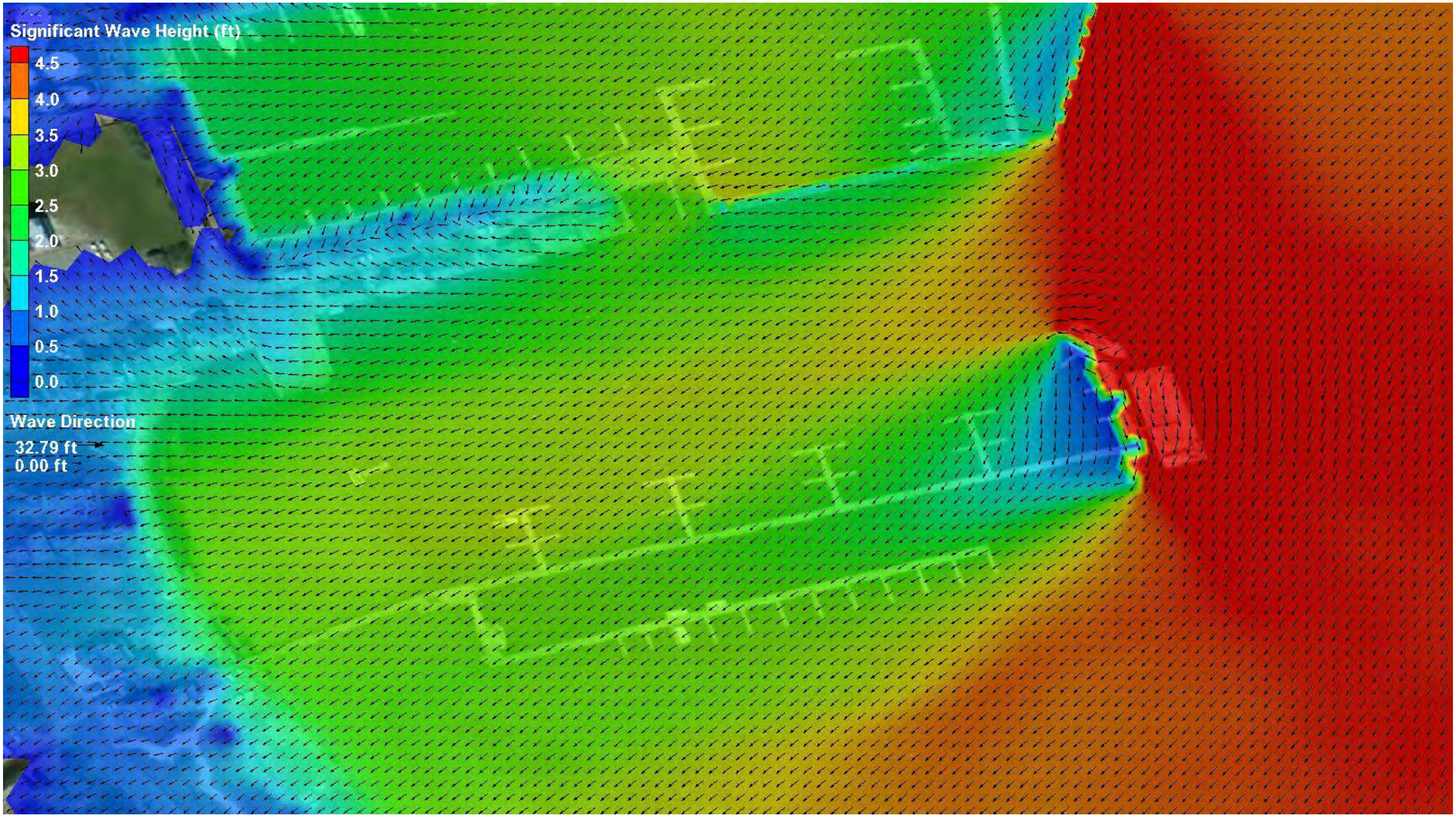

Figure 73: Significant Wave Height simulated by SWAN Wave Model for Run #13B – view 5

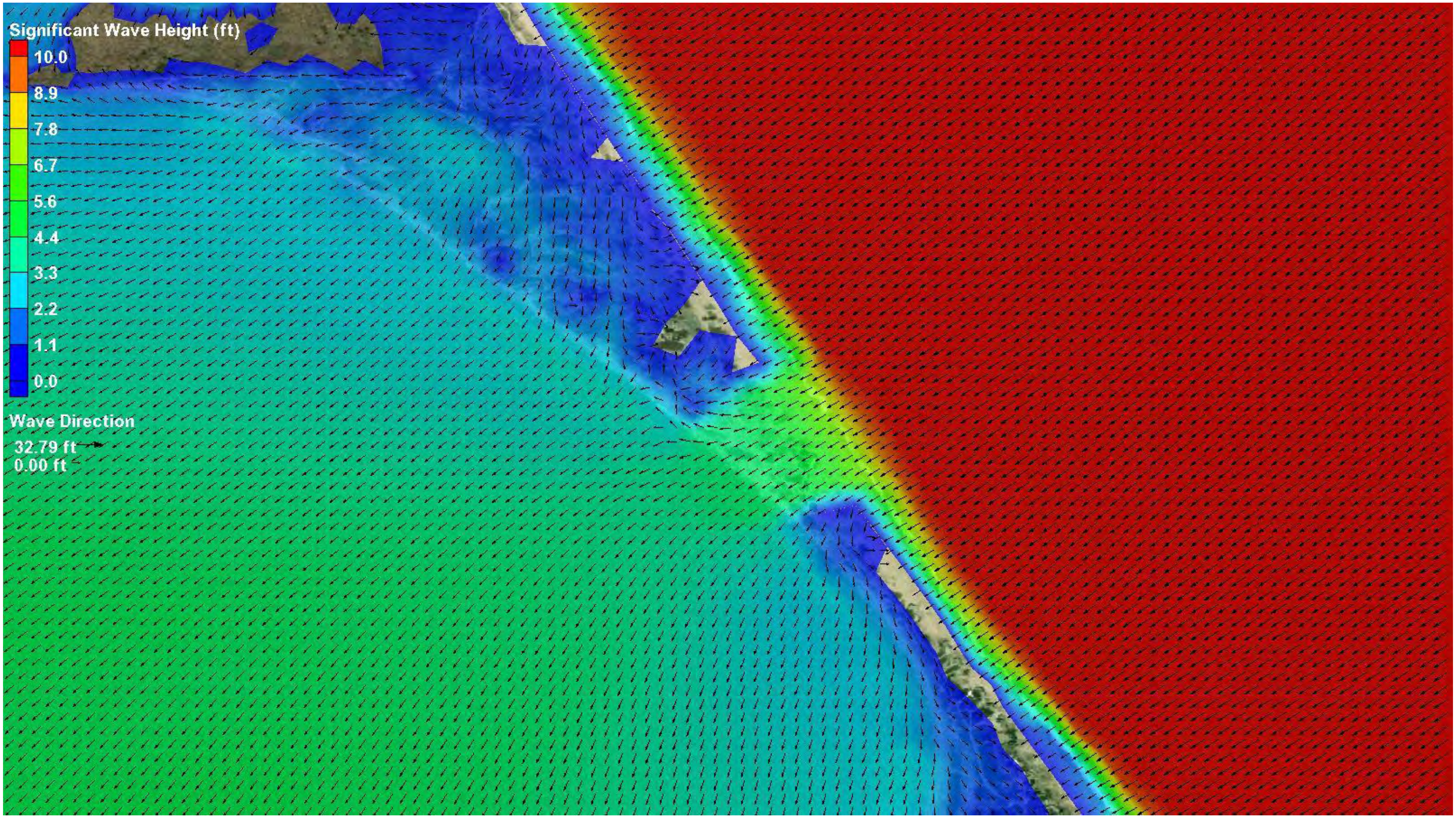

Figure 74: Significant Wave Height simulated by SWAN Wave Model for Run #13B – view 6

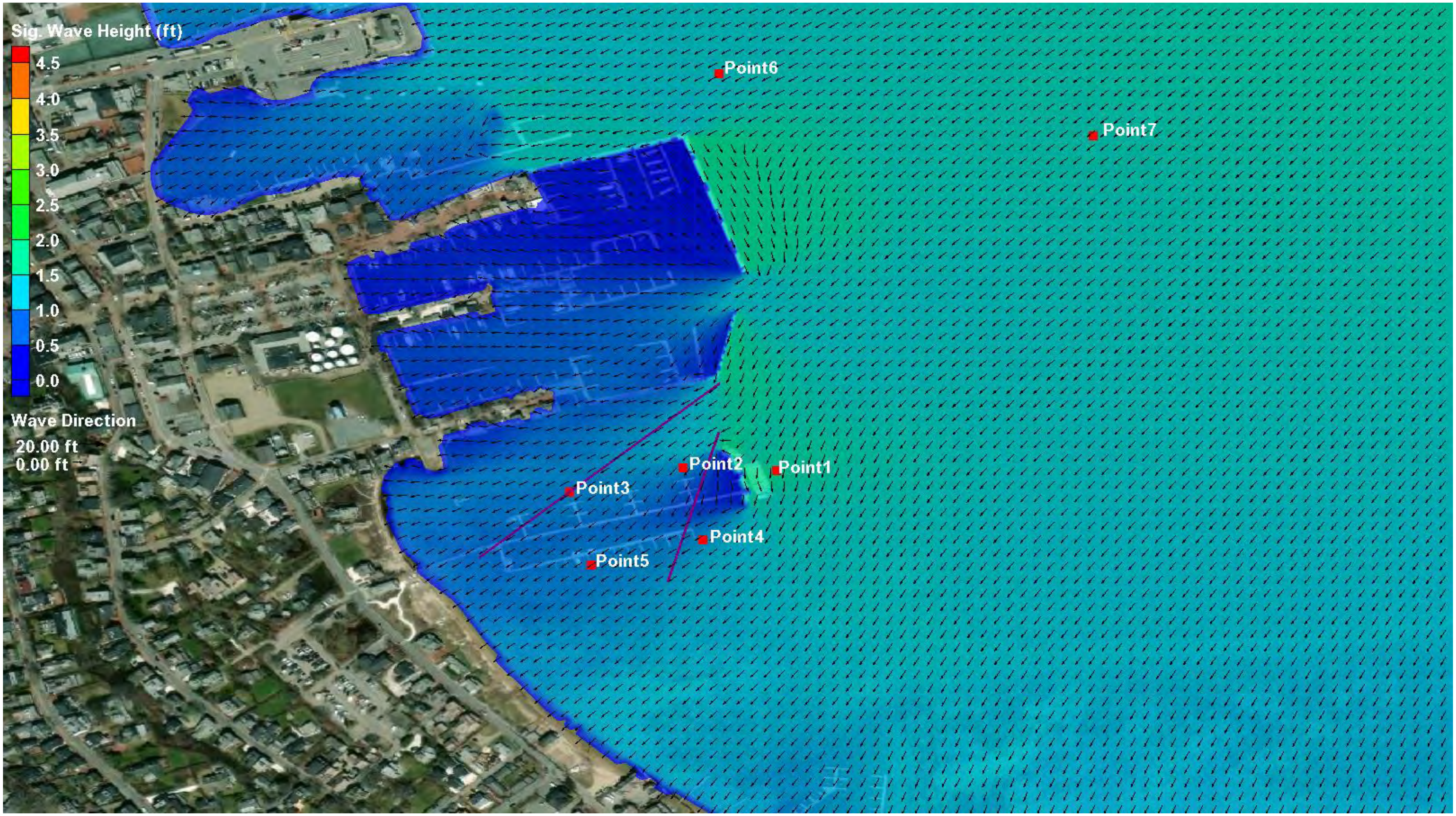

Figure 75: Prevailing Wind Conditions Significant Wave Heights simulated by SWAN Wave Model for Run #20. Purple lines indicate currently observed zone of increased wave height due to adjacent structures.

Model Simulations with Considered Structure Improvements for Comparison

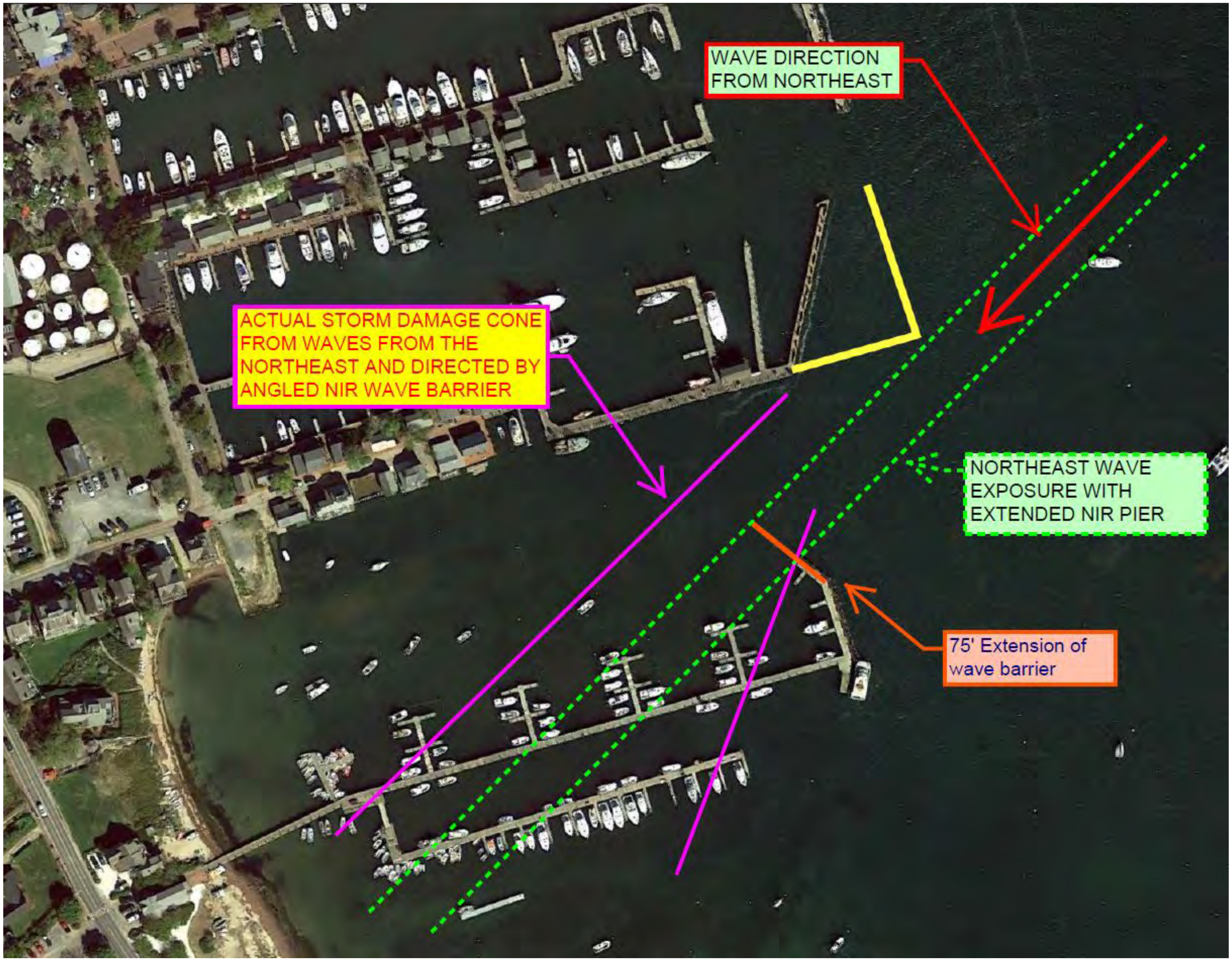

Figure 76: Structure improvements/modifications under consideration including: 1) extension of the existing Town Pier wave fence; and 2) extension of Nantucket Boat Basin. Purple lines indicate currently observed zone of increased wave height due to adjacent structures.

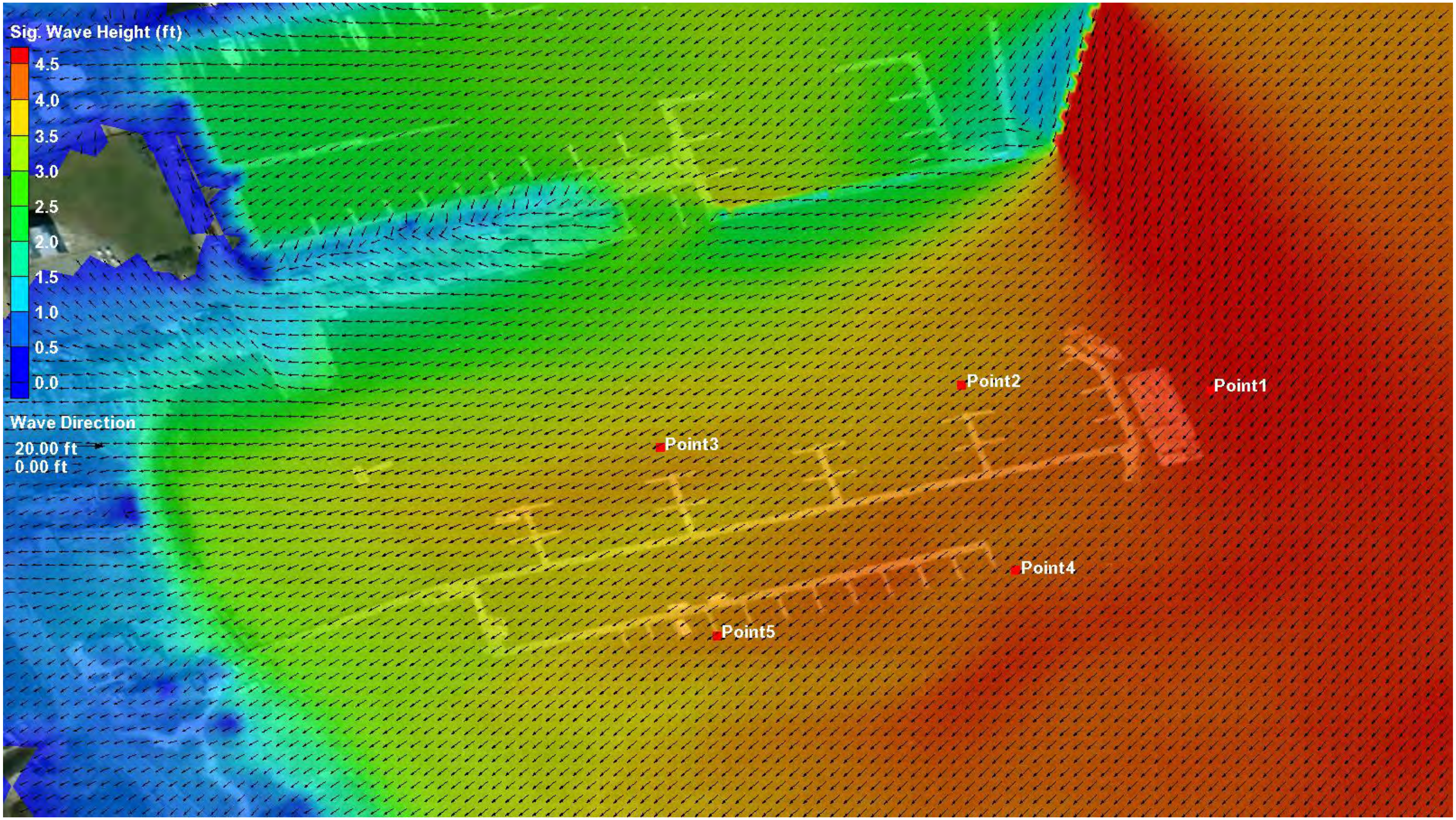

Figure 77: Significant Wave Height simulated by SWAN Wave Model for Run #13D – view 5. Simulation represents a condition without the wave fence in place for comparison.

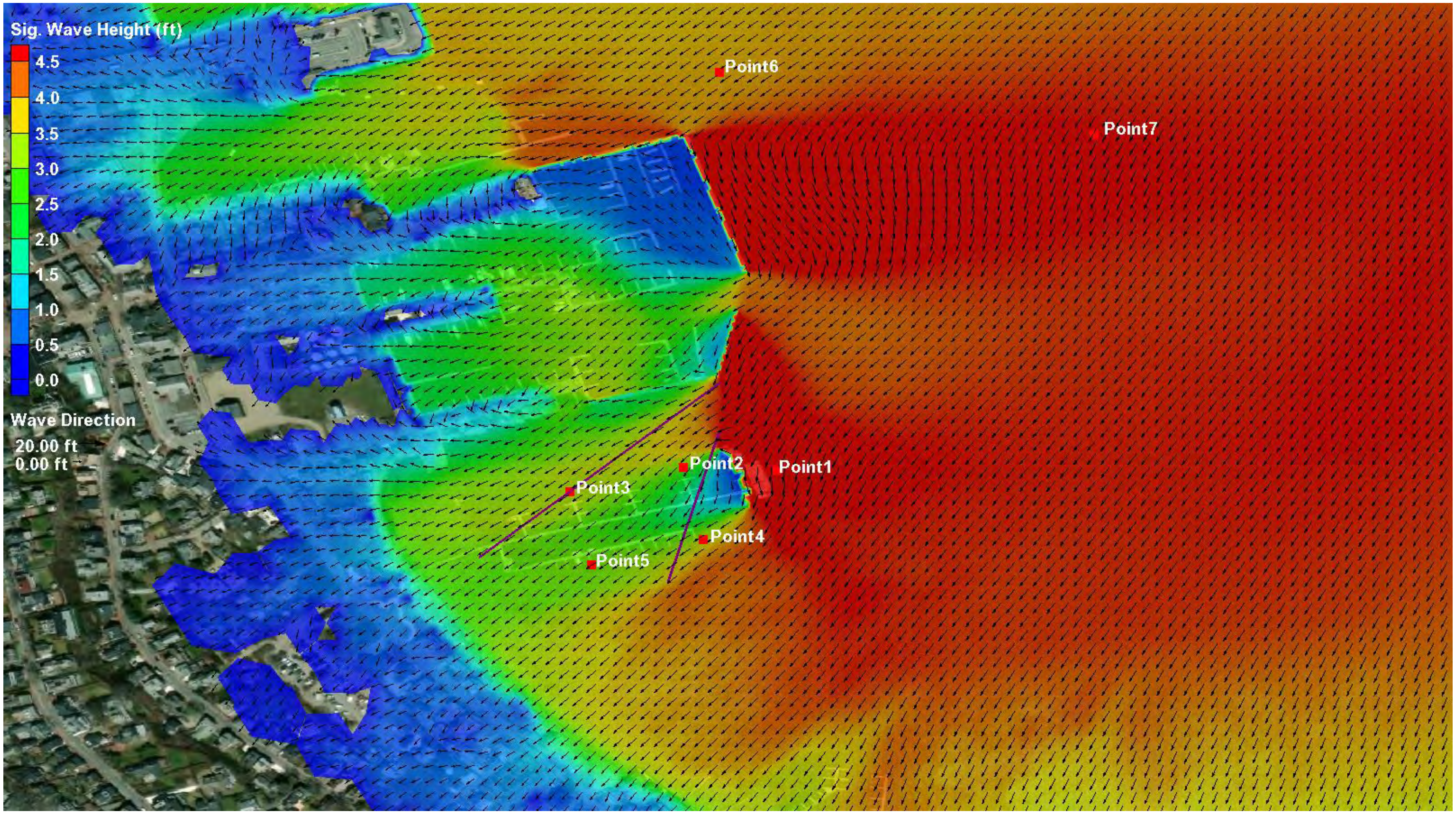

Figure 78: Significant Wave Height simulated by SWAN Wave Model for Run #13. Simulation represents existing condition for comparison.

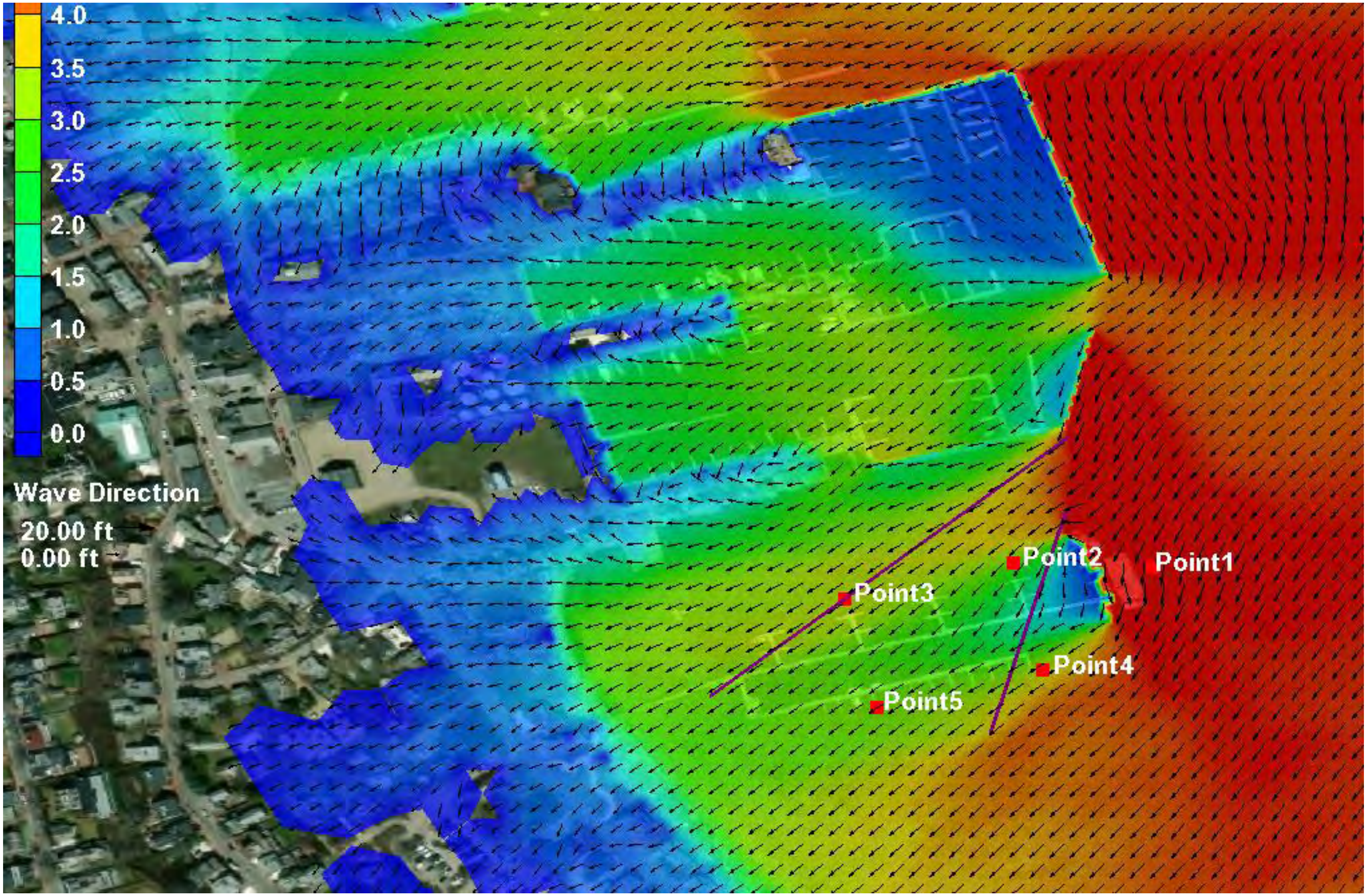

Figure 79: Significant Wave Height simulated by SWAN Wave Model for Run #13. Simulation represents existing condition for comparison. Purple lines indicate currently observed zone of increased wave height due to adjacent structures.

Figure 80: Structure improvements/modifications under consideration including extension of the existing Town Pier wave fence approximately 45 to the north and about 60 feet to the south.

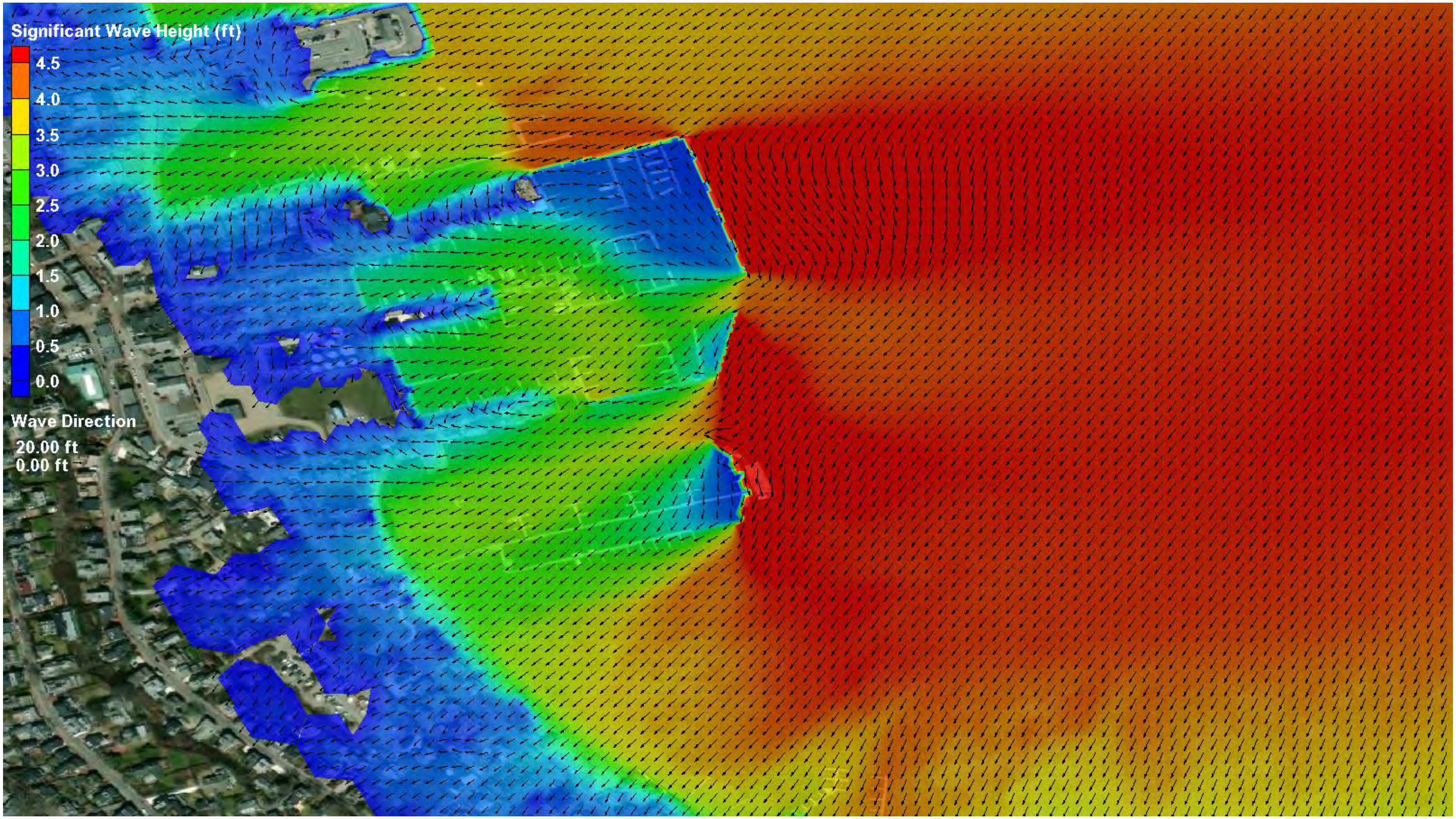

Figure 81: Significant Wave Height simulated by SWAN Wave Model for Run #13C – view 4. Structure improvements/modifications under consideration including extension of the existing Town Pier wave fence approximately 45 to the north and about 60 feet to the south.

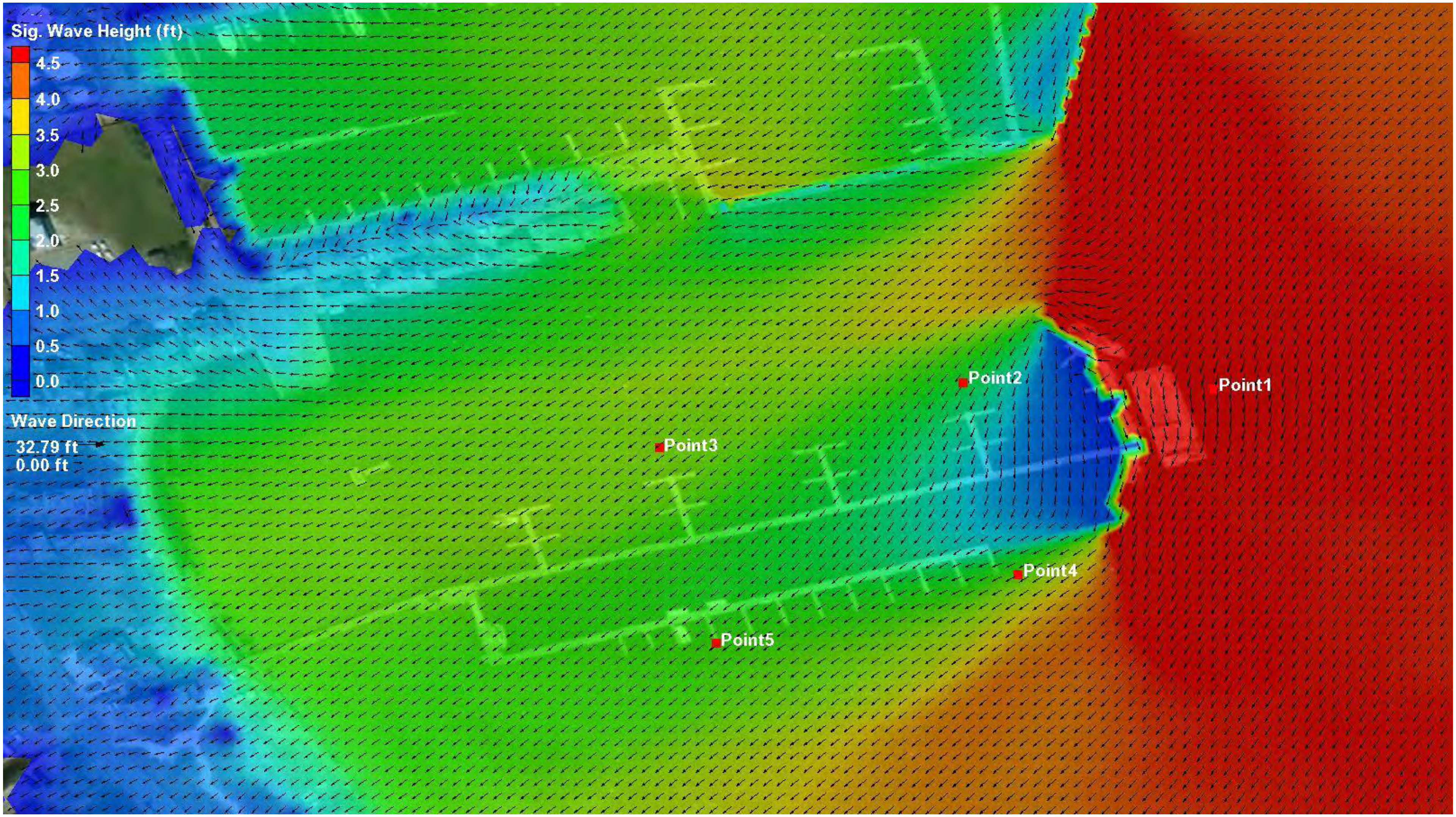

Figure 82: Significant Wave Height simulated by SWAN Wave Model for Run #13C – view 5. Structure improvements/modifications under consideration including extension of the existing Town Pier wave fence approximately 45 to the north and about 60 feet to the south.

Figure 83: Structure improvements/modifications under consideration including extension of the existing Town Pier wave fence approximately 100 feet to the north

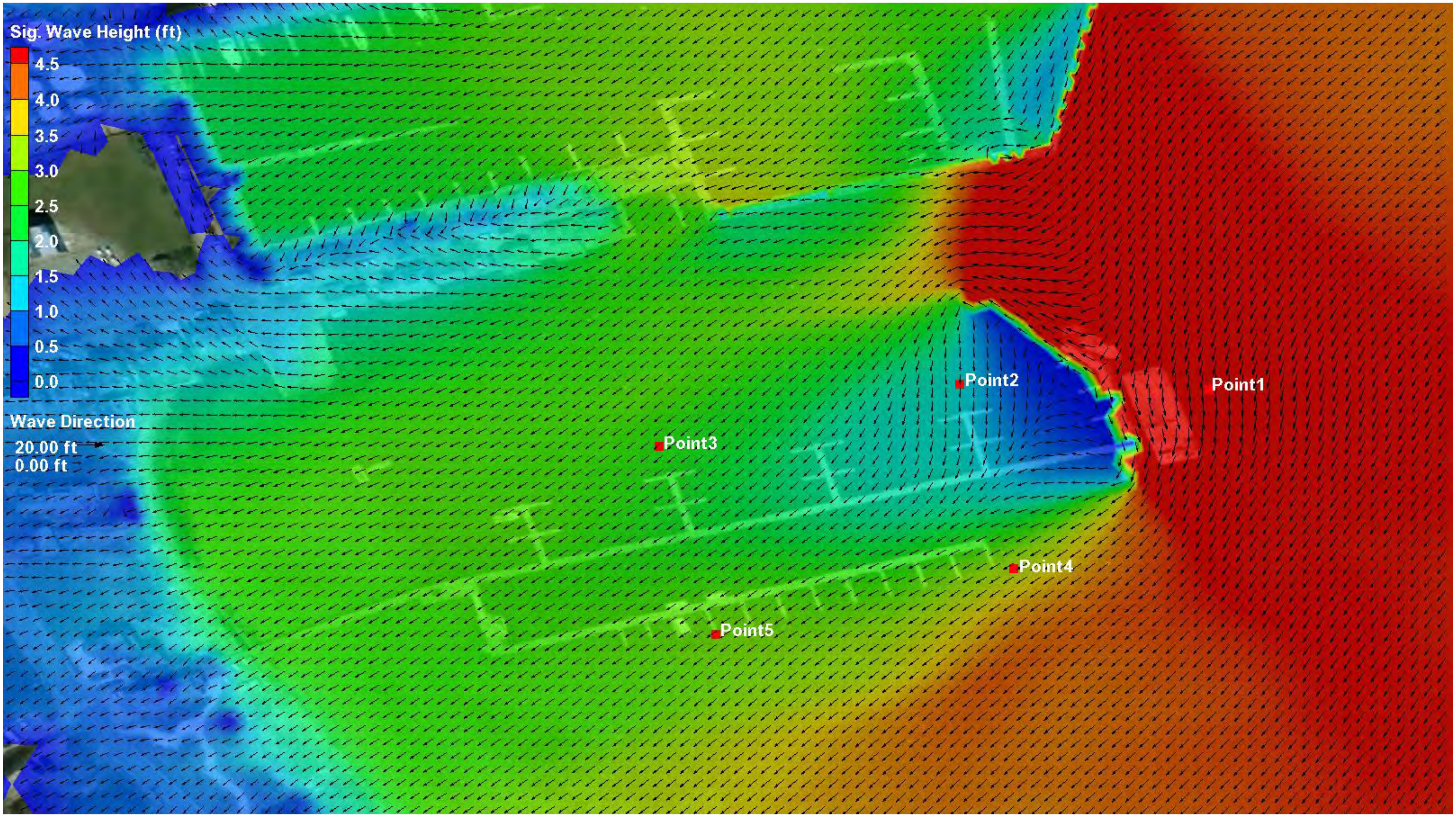

Figure 84: Significant Wave Height simulated by SWAN Wave Model for Run #13E – view 5. Structure improvements/modifications under consideration including extension of the existing Town Pier wave fence approximately 100 feet to the north

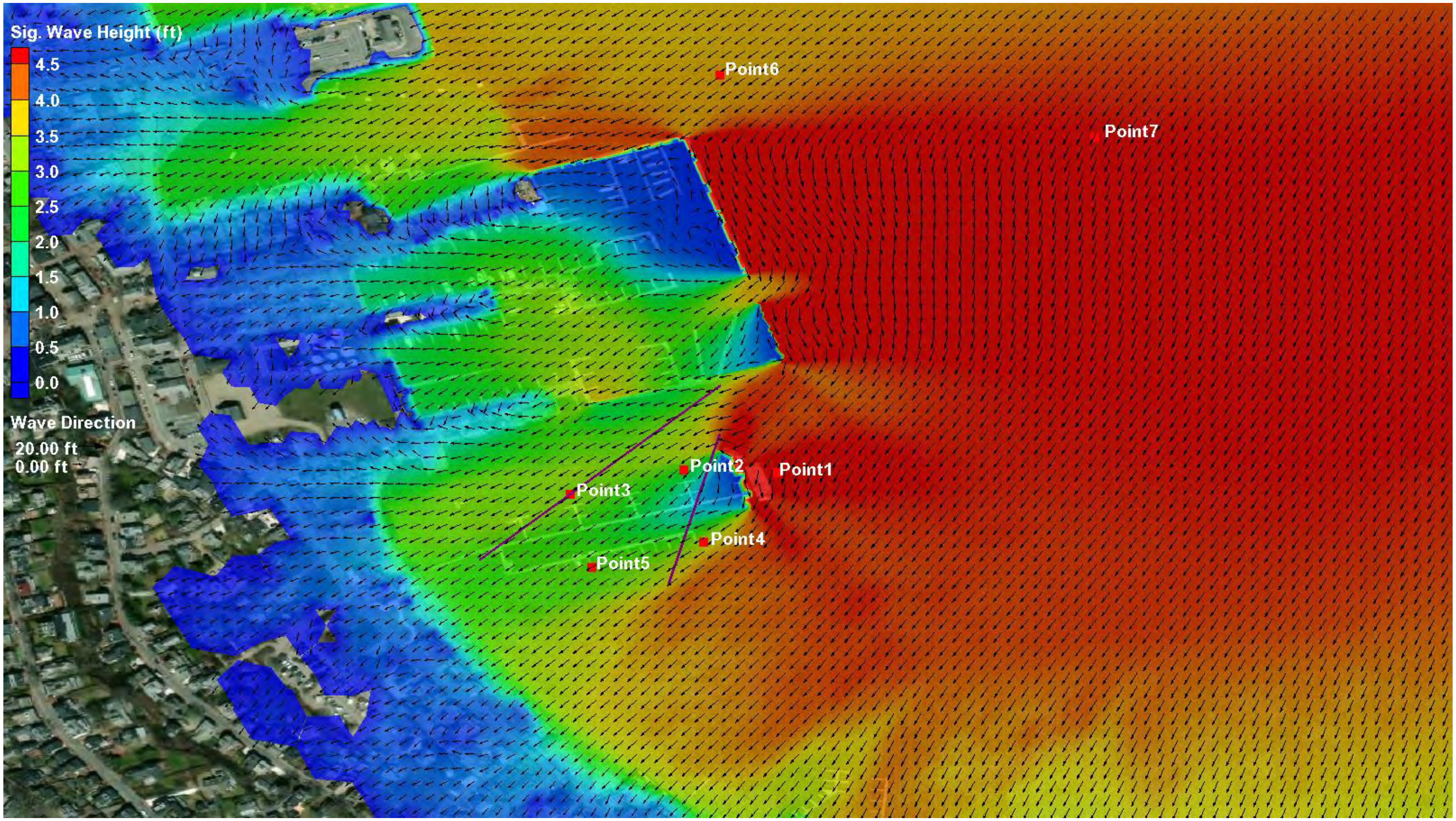

Figure 85: Significant Wave Height simulated by SWAN Wave Model for Run #13F. Structure improvements/modifications under consideration including extension of Nantucket Boat Basin with No Change to Town Pier. Purple lines indicate currently observed zone of increased wave height due to adjacent structures.

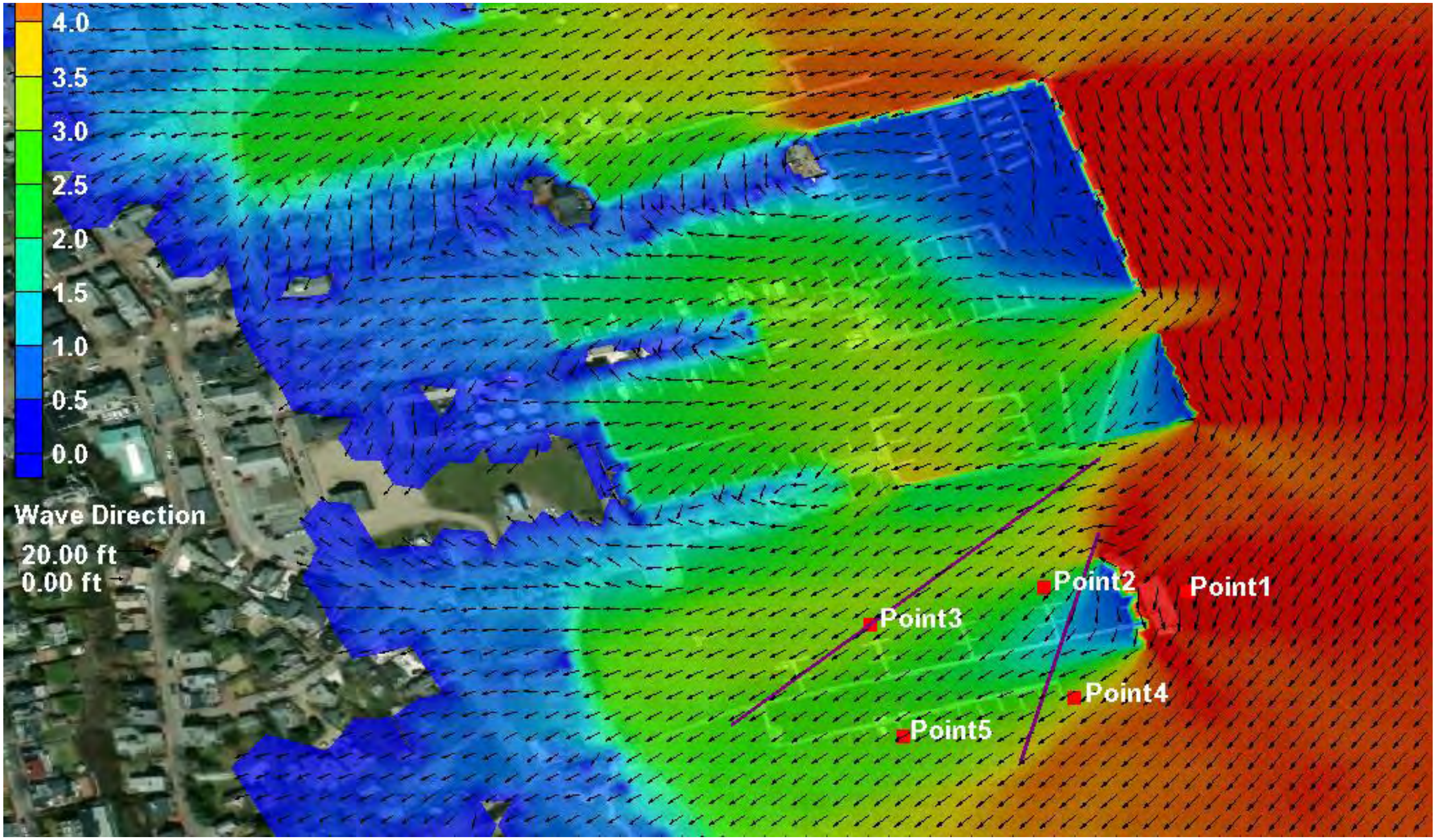

Figure 85: Significant Wave Height simulated by SWAN Wave Model for Run #13F. Structure improvements/modifications under consideration including extension of Nantucket Boat Basin with No Change to Town Pier. Purple lines indicate currently observed zone of increased wave height due to adjacent structures.

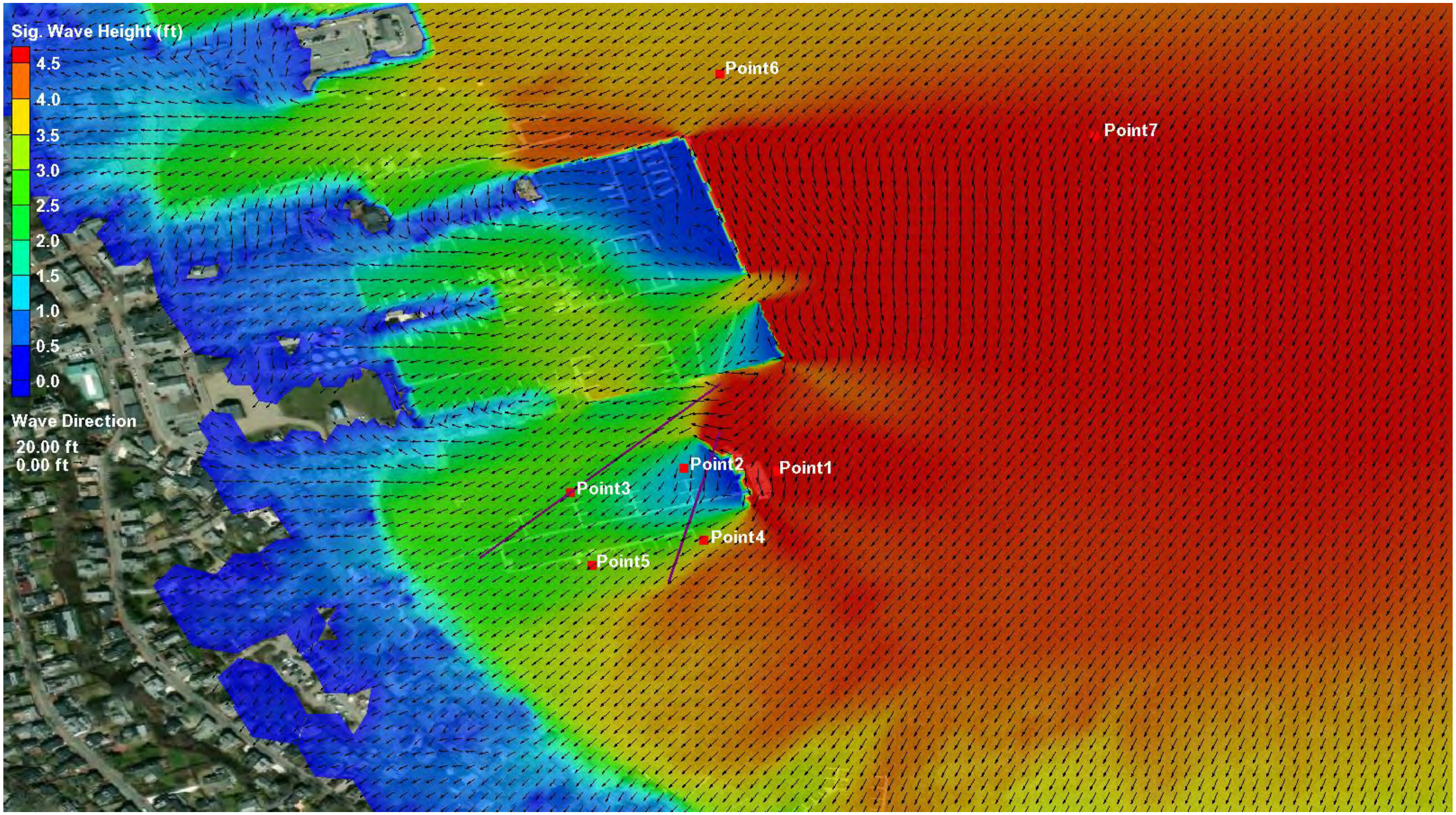

Figure 86: Significant Wave Height simulated by SWAN Wave Model for Run #13G. Structure improvements/modifications under consideration including extension of Nantucket Boat Basin with about north 100-foot extension to Town Pier. Purple lines indicate currently observed zone of increased wave height due to adjacent structures.

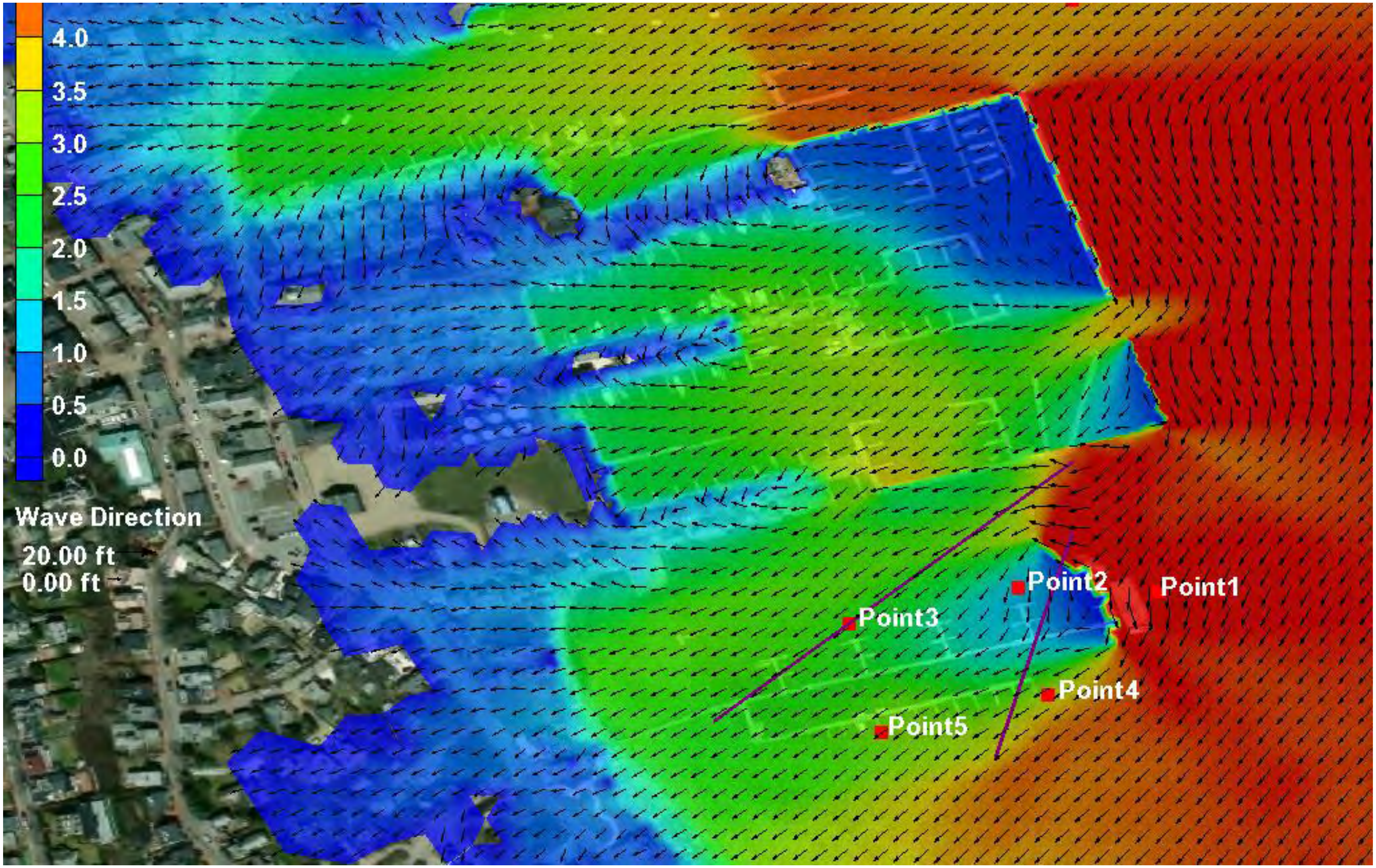

Figure 87: Significant Wave Height simulated by SWAN Wave Model for Run #13G. Structure improvements/modifications under consideration including extension of Nantucket Boat Basin with about north 100-foot extension to Town Pier. Purple lines indicate currently observed zone of increased wave height due to adjacent structures.

ATTACHMENT 7
ASCE Harbor Agitation Guidelines

ASCE Manual 50, 3rd Edition "Planning and Design Guidelines for Small Craft Harbors" presents guidance for tolerable harbor agitation.

Table 2-6. Intermediate Return Period Tranquility Criteria

Generalized Agitation Height (ft) for Intermediate Return Periods			
Return Period	"Excellent" Classification	"Good" Classification	"Moderate" Classification
50 years	$0.75 \times (2 - 1.25\sin\theta)$	$2 - 1.25\sin\theta$	$1.25 \times (2 - 1.25\sin\theta)$
25 years	$0.75 \times (1.75 - 1.05\sin\theta)$	$1.75 - 1.05\sin\theta$	$1.25 \times (1.75 - 1.05\sin\theta)$
10 years	$0.75 \times (1.5 - 0.9\sin\theta)$	$1.5 - 0.9\sin\theta$	$1.25 \times (1.5 - 0.9\sin\theta)$
1 year	$0.75 \times (1 - 0.5\sin\theta)$	$1.0 - 0.5\sin\theta$	$1.25 \times (1 - 0.5\sin\theta)$
1 week	$0.75 \times (0.5 - 0.25\sin\theta)$	$0.5 - 0.25\sin\theta$	$1.25 \times (0.5 - 0.25\sin\theta)$

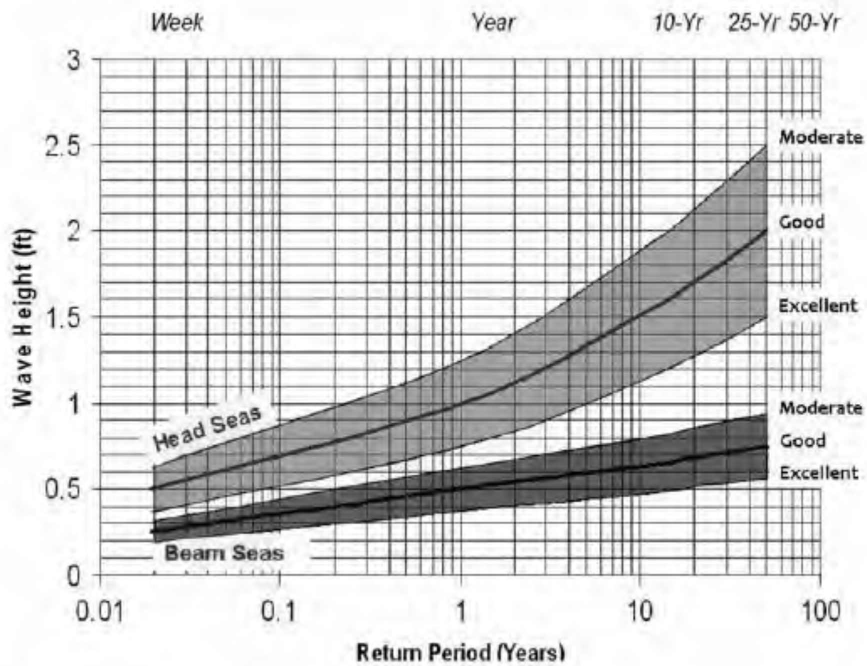

Fig. 2-21. Tolerance for harbor tranquility criterion

ATTACHMENT 8
Probability Analysis

DESIGN APPROACH

In the absence of building structures, the Town Pier design is not regulated under the State Building Code. As such, establishment of the appropriate design criteria is based on acceptable risk. Risk considerations include: 1) the cost of construction versus long term repair and maintenance costs; 2) tolerable operational use under different conditions; and 3) public safety. Risk evaluation requires: 1) defining the intensity of load or event that the pier must accommodate; 2) determining the likelihood of the event; and 3) estimating the chance that the event will occur within a given time period (i.e., the design service life of the Town Pier).

Annual Exceedance Probability (Recurrence Interval)

The environmental conditions that contribute to the pier live loads (i.e., wind, water levels and waves) are characterized in terms of their probability, specifically the annual exceedance probability. This probability can be defined in terms of recurrence interval. For example, a 100-year recurrence interval event has a 1% chance of being met or exceeded in any given year. A 10-year recurrence interval has a 10% chance of being met or exceeded in any given year. A 5-year recurrence interval has a 20% chance of being met or exceeded in any given year. A 1-year recurrence interval has a near 100% chance of being met or exceeded in any given year.

Design Life Encounter Probability

The probability of experiencing an event during the design life of the Town Pier is also an important factor to understand risk. Assuming a 50-year design life (end of service life in the year 2070), the exceedance probabilities (i.e., chance of experiencing the event at least once over the design life are summarized below. For example, the 100-year recurrence interval event has about a 40% chance of occurring at least once during the assumed 50 year design life.

Recurrence Interval (years)	Occurrence Exceedance Probability (%)
5	100.0%
10	99.5%
20	92.3%
50	63.6%
100	39.5%
500	9.5%

Table 1: Probability of Meeting or Exceeding Event during 50 year Design Life

The performance of the pier (and associated repair and replacement costs) is also a function of the effect of multiple storms occurring during the design life. Utilizing a Poisson distribution, the occurrence probabilities for different numbers of events for multiple recurrence intervals and the assumed 50-year design life are summarized below. For example, the 100-year recurrence interval event has about a 40% chance of occurring at least once but is unlikely to occur more than 3 times during the 50-year design life.

Recurrence Interval (years)	No. of Event Occurrences:	1	2	3	4	5	6	7	8	9	10
		Occurrence Probabilities (%)									
5		0.1%	0.2%	0.8%	1.9%	3.8%	6.3%	9.0%	11.3%	12.5%	12.5%
10		3.4%	8.4%	14.4%	17.6%	17.6%	14.6%	10.4%	6.5%	3.6%	1.8%
20		20.5%	25.6%	21.4%	13.4%	6.7%	2.8%	1.0%	0.3%	0.1%	0.0%
50		36.8%	18.4%	6.1%	1.5%	0.3%	0.1%	0.1%	0	0	0
100		30.3%	7.6%	1.3%	1.6%	0.2%	0	0	0	0	0
500		9.1%	0.5%	0	0	0	0	0	0	0	0

Table 2: Probability of Multiple Events during 50 year Design Life

The probability of multiple events is also often presented in terms of cumulative probability. That is, for example, the chance that an event will occur 1 or more time, 2 or more times, 3 or more times, etc. These probabilities are presented below.

Recurrence Interval (years)	≥ No. of Event Occurrences:	1	2	3	4	5	6	7	8	9	10
5		100.0%	99.9%	99.7%	99.0%	97.1%	93.3%	87.0%	78.0%	78.0%	54.2%
10		99.5%	96.1%	87.7%	73.3%	55.7%	38.2%	23.6%	13.1%	6.6%	3.0%
20		92.3%	71.8%	46.2%	24.8%	11.4%	4.7%	1.9%	0.9%	0.6%	0.3%
50		63.6%	26.8%	8.4%	2.3%	0.7%	0.4%	0.4%	0.3%	0.3%	0.3%
100		39.5%	9.2%	1.6%	0.3%	0.0%	0	0	0	0	0
500		9.5%	0.5%	0	0	0	0	0	0	0	0

Table 3: Probability of Meeting or Exceeding Multiple Events during 50 year Design Life

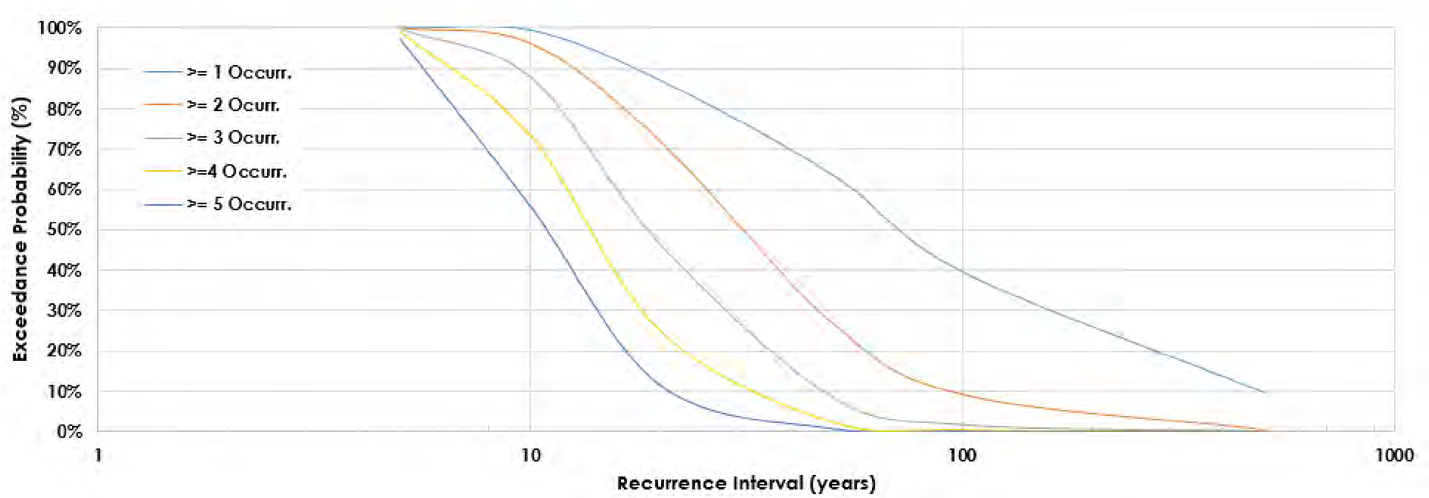

Figure 1: Probability of Meeting or Exceeding Multiple Events during 50 year Design Life

Design Life Encounter Probability – Environmental Conditions

The encounter probabilities described above can be applied to the specific environmental conditions (wind, water level, waves) predicted at Nantucket Harbor. The annual exceedance probabilities (i.e., recurrence intervals) for each of these conditions are presented in other attachments: Wind in **Attachment 4**, Water Levels in **Attachment 5** and Waves in **Attachment 6**.

The individual probabilities for wind and water level have been established. The correlation between these probabilities is relevant to the joint probability of experienced combined effects (i.e., a water level probability combined with a wind probability combined with a wave probability). As demonstrated by GZA's numerical wave modeling, wave generation within Nantucket Harbor is due to wind-generated wave conditions within the harbor and limited by fetch, duration and depth). That is, waves within the harbor are not influenced by ocean waves or swells. Therefore, wind intensity and wave height are directly correlated for evaluation of the Town Pier. As shown in Attachment 5, extreme water levels (i.e., due to storm surge) are generally correlated with elevated wind speeds. For example, elevated wind and waves within Nantucket Harbor are typically the result of nor'easters which also simultaneously generate storm surge and elevated water levels. For design of the Town Pier improvements, it is conservatively assumed that the extreme wind, waves and water levels are dependent events and are directly correlated.

The design life encounter probabilities for the current climate mean stillwater elevation (from **Attachment 5)** and maximum significant wave height (from **Attachment 6**) predicted at the Town Pier are summarized below.

Table 4 summarizes the exceedance probabilities of the current-climate stillwater elevations (based on USACE NACCS) data and for a range of multiple events. The mean values are presented. The estimation of the stillwater elevation, at each recurrence interval, includes error and uncertainty. The 95% upper confidence level (representing the uncertainty - or reliability - of the estimated mean stillwater elevation at each recurrence interval, developed assuming a Gaussian distribution of epistemic uncertainty) estimated by the USCE NACCS study are also presented. **Table 5** summarizes the multiple event exceedance probabilities of the current-climate mean stillwater elevation.

Recurrence Interval (years)	Occurrence Exceedance Probability (%)	Mean Stillwater Elevation (feet, NAVD88)	95% Upper Confidence Level Stillwater Elevation (feet, NAVD88)
5	100.0%	3.3	7.4
10	99.5%	4.8	7.8
20	92.3%	5.2	8.3
50	63.6%	5.5	9.0
100	39.5%	5.8	9.4
500	9.5%	6.9	10.8

Table 4: Stillwater Exceedance Probabilities for Mean and Upper Bound Values

		≥ No. of Storm Occurrences									
Recurrence Interval (years)	Mean Stillwater Elevation (feet, NAVD88)	1	2	3	4	5	6	7	8	9	10
5	3.3	100.0%	99.9%	99.7%	99.0%	97.1%	93.3%	87.0%	78.0%	78.0%	54.2%
10	4.8	99.5%	96.1%	87.7%	73.3%	55.7%	38.2%	23.6%	13.1%	6.6%	3.0%
20	5.2	92.3%	71.8%	46.2%	24.8%	11.4%	4.7%	1.9%	0.9%	0.6%	0.3%
50	5.5	63.6%	26.8%	8.4%	2.3%	0.7%	0.4%	0.4%	0.3%	0.3%	0.3%
100	5.8	39.5%	9.2%	1.6%	0.3%	0.0%	0	0	0	0	0
500	6.9	9.5%	0.5%	0	0	0	0	0	0	0	0

Table 5: Probability of Meeting or Exceeding Mean Stillwater Multiple Events during 50 year Design Life

The largest significant wave heights (H_s) and maximum wave height (H_{max}) predicted at the Town Pier (for two different wind sources) are developed in **Attachment 6**, and presented in **Figure 2**. The wave heights (unless depth-limited) experienced during a storm event are assumed to be randomly distributed consistent with a Rayleigh distribution. The significant wave height (Hs) is the average of the top third of the waves and has about a 13% probability of being exceeded. The average of the highest 10% of the waves (H_{10}) has about a 4% exceedance probability and is equal to about 1.27 x H_s. The average of the highest 1% of the waves (H_{10}) has about a 0.35% exceedance probability and is equal to about 1.68 x H_s. H_{max} is approximately the top 0.1% of the waves and is equal to about 2 x H_s. **Table 6** summarizes the multiple event exceedance probabilities of the current-climate maximum significant wave heights (H_s).

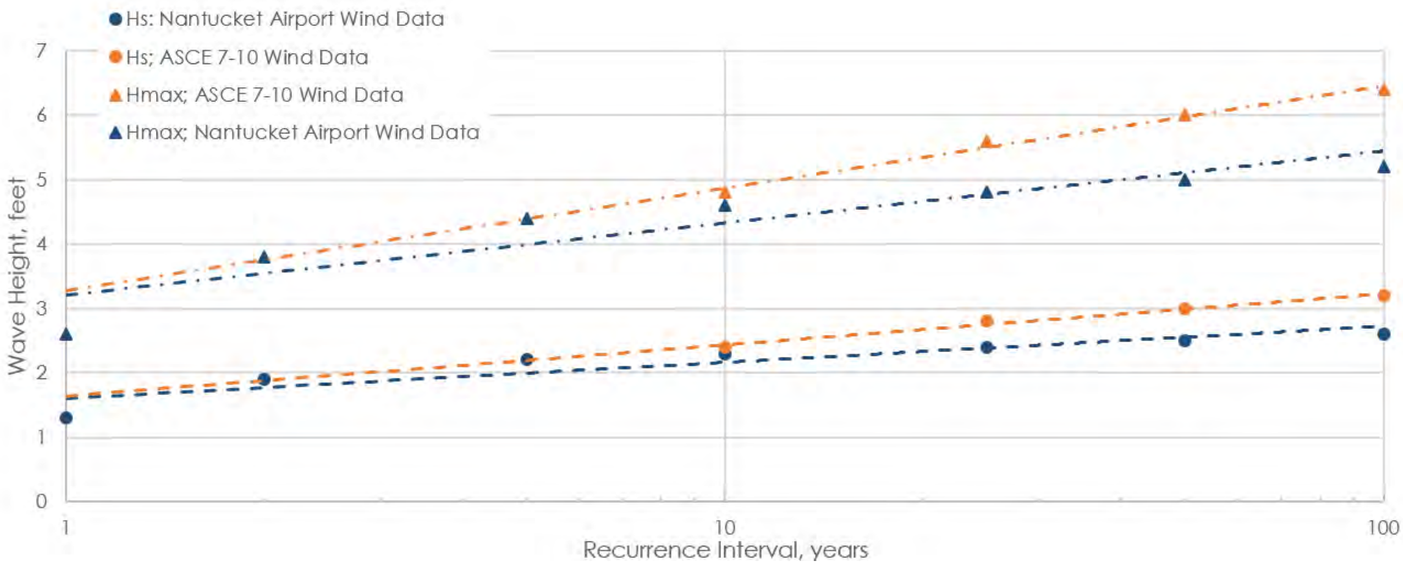

Figure 2: Predicted Wave Heights versus Recurrence Interval

		≥ No. of Storm Occurrences									
Recurrence Interval (years)	Maximum Significant Wave height (feet)	1	2	3	4	5	6	7	8	9	10
5	2.2	100.0%	99.9%	99.7%	99.0%	97.1%	93.3%	87.0%	78.0%	78.0%	54.2%
10	2.3	99.5%	96.1%	87.7%	73.3%	55.7%	38.2%	23.6%	13.1%	6.6%	3.0%
25	2.4	92.3%	71.8%	46.2%	24.8%	11.4%	4.7%	1.9%	0.9%	0.6%	0.3%
50	2.5	63.6%	26.8%	8.4%	2.3%	0.7%	0.4%	0.4%	0.3%	0.3%	0.3%
100	2.6	39.5%	9.2%	1.6%	0.3%	0.0%	0	0	0	0	0

Table 6: Probability of Meeting or Exceeding Multiple Wave Events during 50 year Design Life (Nantucket Airport Wind Data)

		≥ No. of Storm Occurrences									
Recurrence Interval (years)	Maximum Significant Wave height (feet)	1	2	3	4	5	6	7	8	9	10
5	-	100.0%	99.9%	99.7%	99.0%	97.1%	93.3%	87.0%	78.0%	78.0%	54.2%
10	2.4	99.5%	96.1%	87.7%	73.3%	55.7%	38.2%	23.6%	13.1%	6.6%	3.0%
25	2.8	92.3%	71.8%	46.2%	24.8%	11.4%	4.7%	1.9%	0.9%	0.6%	0.3%
50	3.0	63.6%	26.8%	8.4%	2.3%	0.7%	0.4%	0.4%	0.3%	0.3%	0.3%
100	3.2	39.5%	9.2%	1.6%	0.3%	0.0%	0	0	0	0	0

Table 7: Probability of Meeting or Exceeding Multiple Wave Events during 50 year Design Life (ASCE 7-10 Wind Speed)

Wave Distribution

The statistics of wave heights in the random sea are assumed to follow the Rayleigh Probability Distribution, and the significant wave heights (H_s) presented here indicate the average of the top 1/3 of the waves in the random sea. Based on the Rayleigh distribution, the statistics of wave heights are characterized as: $H_{1/10}$ is the average of the top 10% of the waves (= 1.27 x H_s); $H_{1/100}$ is the average of the top 1% of the waves (= 1.67 x Hs); H_{max} is the maximum wave height (= 2.0 x H_s). The associated cumulative exceedance wave probabilities are: H_s is 13.5%; $H_{1/10}$ is 3.9%; and $H_{1/100}$ is 0.35%.

Wave Crest Elevation

The wave crest elevation is the elevation of the top of the wave crest and is a function of the total water level (stillwater elevation plus wave set-up), wave height and the portion of the wave occurring above the total water (or stillwater) level is dependent upon the wave characteristics and shoaling effects is determined as follows. For depth-limited and steep waves, about 70% of the wave height is above the stillwater level. **Figure 3** presents wave crest elevation versus recurrence interval.

Recurrence Interval (years)	Stillwater Elevation (feet; NAVD88)	Total Water Elevation (feet; NAVD88)	Wave Crest Elevation (H_s; feet NAVD88)	Wave Crest Elevation ($H_{1/10}$; feet NAVD88)	Wave Crest Elevation ($H_{1/100}$; feet NAVD88)	Wave Crest Elevation (H_{max}; feet NAVD88
Wave Distribution Exceedance Probability			13.5%	3.9%	0.4%	-
5	3.3	3.8	5.3	5.8	6.4	6.9
10	4.8	5.3	6.9	7.4	8.1	8.5
25	5.3	5.8	7.5	7.9	8.6	9.2
50	5.6	6.1	7.9	8.3	9.0	9.6
100	5.8	6.3	8.1	8.6	9.3	10.0

Table 8: Wave Height Distribution versus Recurrence Interval (Nantucket Airport Wind Data)

Recurrence Interval (years)	Stillwater Elevation (feet; NAVD88)	Total Water Elevation (feet; NAVD88)	Wave Crest Elevation (H_s; feet NAVD88)	Wave Crest Elevation ($H_{1/10}$; feet NAVD88)	Wave Crest Elevation ($H_{1/100}$; feet NAVD88)	Wave Crest Elevation (H_{max}; feet NAVD88
Wave Distribution Exceedance Probability			13.5%	3.9%	0.4%	-
5	3.3	3.8	-	-	-	-
10	4.8	5.3	7.0	7.4	8.1	8.7
25	5.3	5.8	7.8	8.3	9.1	9.7
50	5.6	6.1	8.2	8.8	9.6	10.3
100	5.8	6.3	8.5	9.1	10.0	10.8

Table 9: Wave Height Distribution versus Recurrence Interval (ASCE 7-10 Wind Data)

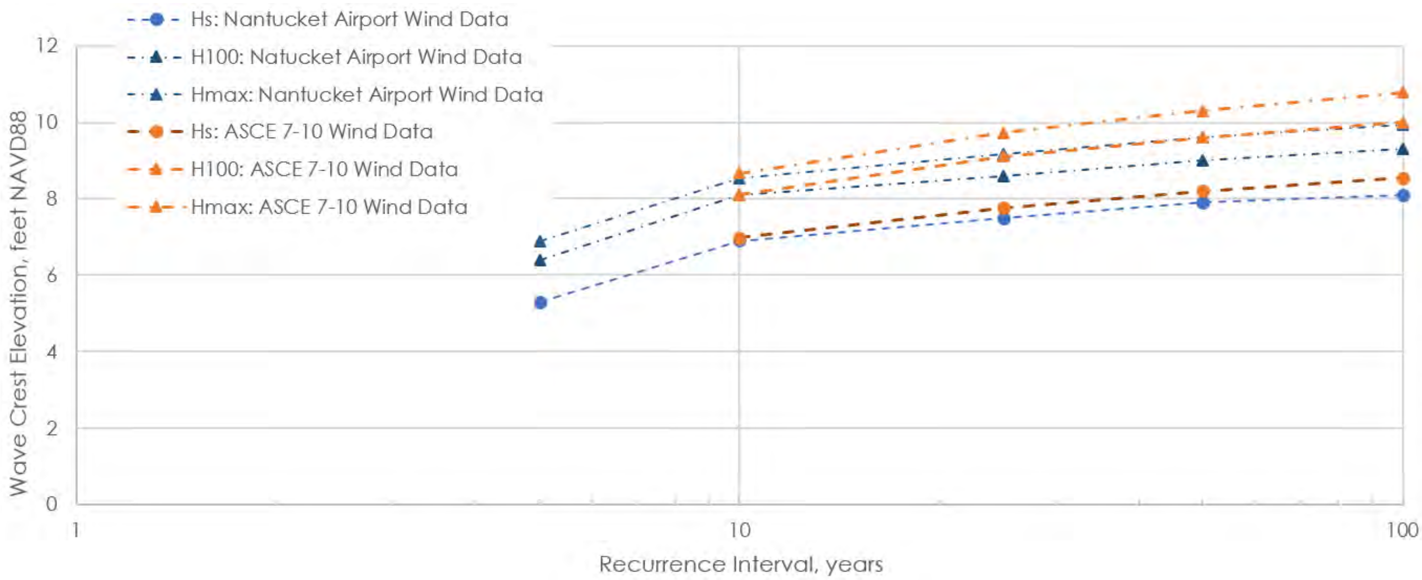

Figure 3: Predicted Wave Crest Elevation versus Recurrence Interval

Design Life Encounter Probability – Effect of Sea Level Rise

The effect of sea level rise will be to increase the frequency (and/or magnitude) of future flood stillwater elevations. GZA's numerical wave modeling indicates that there will be minimal effect of sea level rise on wave heights. While historic sea levels (over the last 100 years) have been observed to be rising, the projection of the rate of future sea level is uncertain. Currently, several future sea level rise projections have been developed, reflecting different future climate scenarios (defined within Representative Concentration Pathways). See **Attachment 6** for details. Based on the estimated probabilities associated with each of the future climate scenarios (Representative Concentration Pathways), future sea level rise at Nantucket can currently be characterized as follows for the year 2100 relative to the year 2000 (**Figure 4**; Kopp et al., 2014 – see **Attachment 6**). Although there is significant uncertainty, for planning purposes extrapolations of these probabilities to other time periods, relative to the year 2020, representing the design life of the Town Pier improvements are presented in **Figures 5** through **7**.

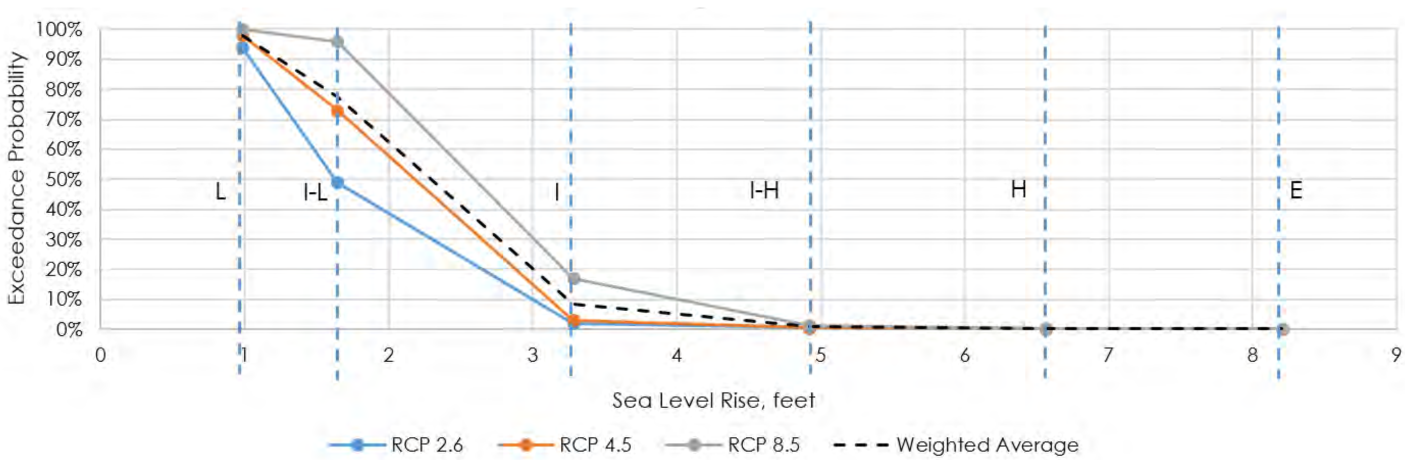

Figure 4: Year 2100 NOAA 2017 Projected Sea Level Rise at Nantucket Exceedance Probabilities for different Representative Concentration Pathways

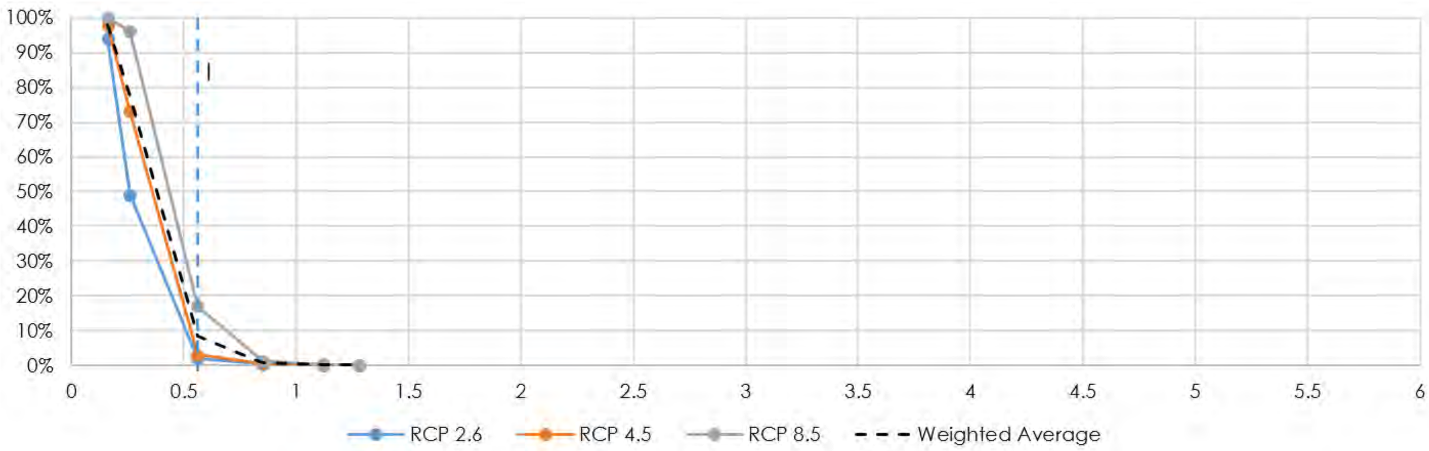

Figure 5: Year 2030 NOAA 2030 Projected Sea Level Rise at Nantucket Exceedance Probabilities for different Representative Concentration Pathways. See Figure 4 for axis descriptions.

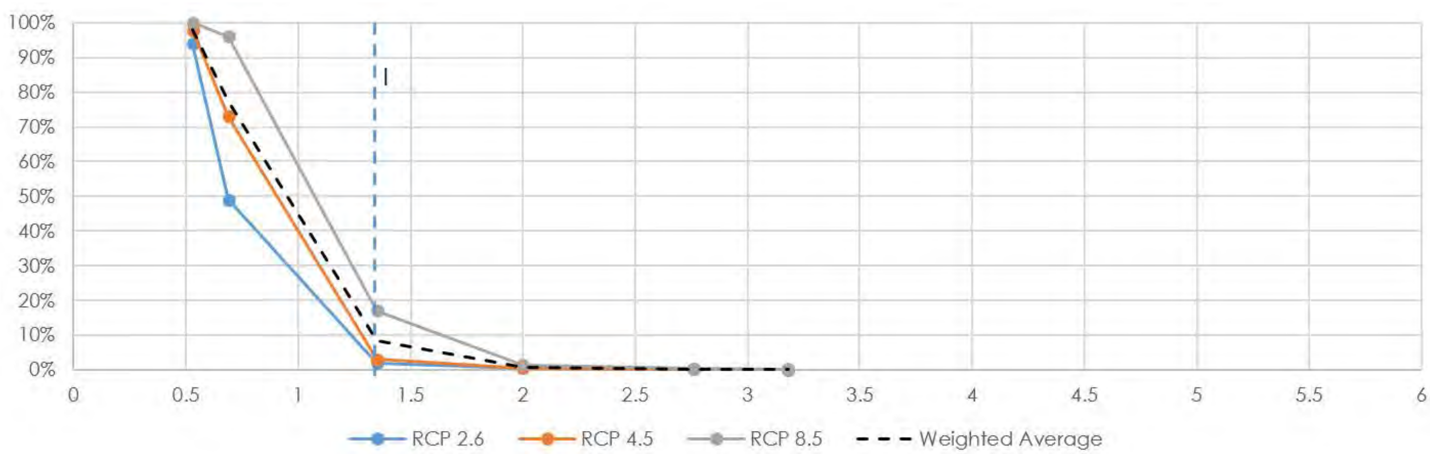

Figure 6: Year 2050 NOAA 2050 Projected Sea Level Rise at Nantucket Exceedance Probabilities for different Representative Concentration Pathways. See Figure 4 for axis descriptions.

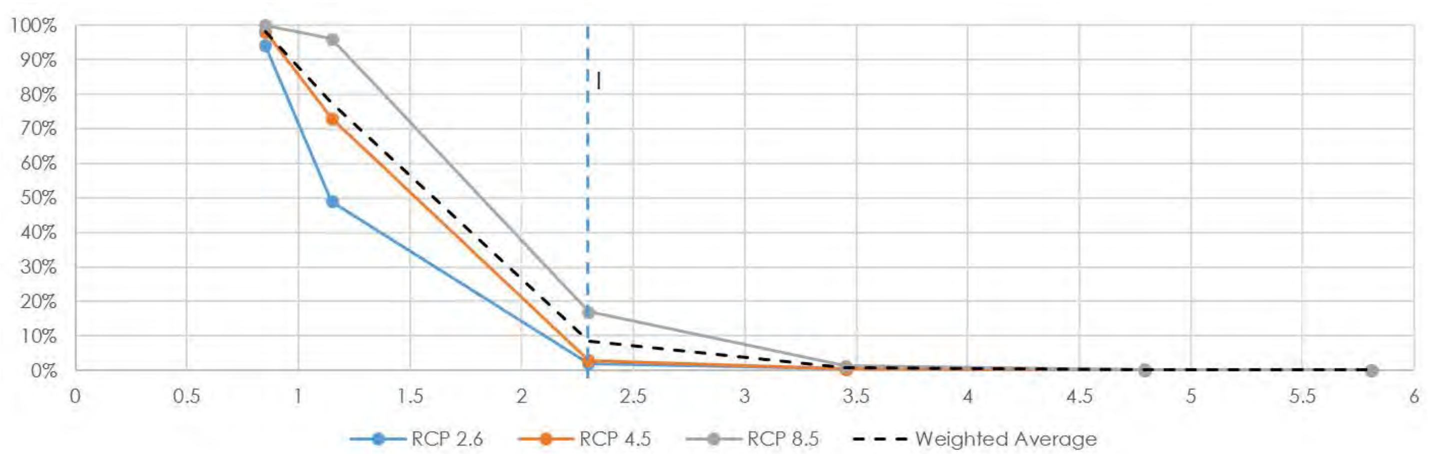

Figure 7: Year 2070 NOAA 2070 Projected Sea Level Rise at Nantucket Exceedance Probabilities for different Representative Concentration Pathways. See Figure 4 for axis descriptions.

Most of the projected sea level rise probability mass is located between the NOAA 2017 Intermediate-Low and Intermediate projections. Assuming a weighted average risk curve (RCP2.6 at 20%; RCP4.5 at 40% and RCP8.5 at 40%), **Figure 8** presents the predicted sea leve rise probabilities during the Town Pier improvement design life ssuming the NOAA2017 Intermediate projection.

Sea level rise is an independent parameter in terms of combined effects with storm surge and tide. This means that the joint probability of stillwater elevation and sea level rise is lower for the lower probability sea level rise projections. A reasonable assumption is to utilize the NOAA 2017 Intermediate projection with an assumed probability of 1.0.

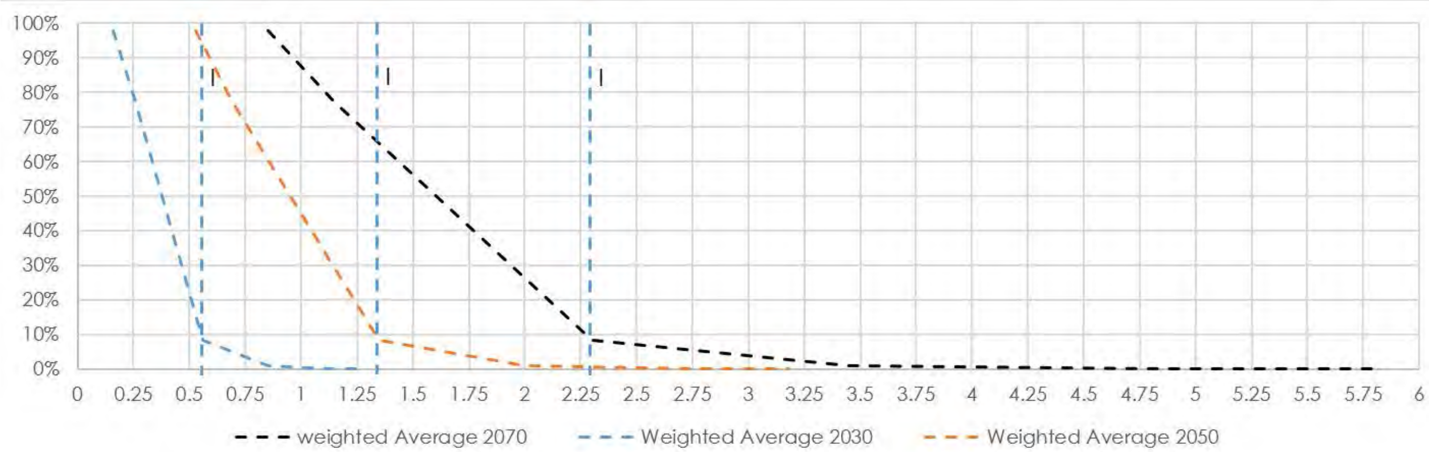

Figure 8: NOAA 2070 Projected Sea Level Rise at Nantucket during Town Pier Improvements Design Life. See Figure 3 for axis descriptions.

Sea level rise can reasonably be linearly superimposed on the predcited stillwater and total water levels. The effects on predicted wave crest elevation, assuming the NOAA 2017 Intermediate projection are summarized below:

Year 2030:

Recurrence Interval (years)	Stillwater Elevation (feet; NAVD88)	Total Water Elevation (feet; NAVD88)	Wave Crest Elevation (Hs; feet NAVD88)	Wave Crest Elevation ($H_{1/10}$; feet NAVD88)	Wave Crest Elevation ($H_{1/100}$; feet NAVD88)	Wave Crest Elevation (H_{max}; feet NAVD88)
Wave Distribution Exceedance Probability			13.5%	3.9%	0.4%	-
5	3.9	4.4	5.9	6.3	6.9	7.4
10	5.4	5.9	7.5	7.9	8.6	9.1
25	5.9	6.4	8.1	8.5	9.2	9.7
50	6.2	6.7	8.4	8.9	9.6	10.2
100	6.4	6.9	8.7	9.2	9.9	10.5

Table 10: Year 2030 Wave Height Distribution versus Recurrence Interval (Nantucket Airport Wind Data)

Recurrence Interval (years)	Stillwater Elevation (feet; NAVD88)	Total Water Elevation (feet; NAVD88)	Wave Crest Elevation (H_s; feet NAVD88)	Wave Crest Elevation ($H_{1/10}$; feet NAVD88)	Wave Crest Elevation ($H_{1/100}$; feet NAVD88)	Wave Crest Elevation (H_{max}; feet NAVD88)
Wave Distribution Exceedance Probability			13.5%	3.9%	0.4%	-
5	3.9	4.4	-	-	-	-
10	5.4	5.9	7.5	8.0	8.7	9.2
25	5.9	6.4	8.3	8.9	9.6	10.3
50	6.2	6.7	8.8	9.3	10.2	10.9
100	6.4	6.9	9.1	9.7	10.6	11.3

Table 11: Year 2030 Wave Height Distribution versus Recurrence Interval (ASCE 7-10 Wind Data)

Year 2050:

Recurrence Interval (years)	Stillwater Elevation (feet; NAVD88)	Total Water Elevation (feet; NAVD88)	Wave Crest Elevation (H_s; feet NAVD88)	Wave Crest Elevation ($H_{1/10}$; feet NAVD88)	Wave Crest Elevation ($H_{1/100}$; feet NAVD88)	Wave Crest Elevation (H_{max}; feet NAVD88)
Wave Distribution Exceedance Probability			13.5%	3.9%	0.4%	-
5	4.7	5.2	6.7	7.2	7.7	8.2
10	6.2	6.7	8.3	8.7	9.4	9.9
25	6.7	7.2	8.8	9.3	10.0	10.5
50	7.0	7.5	9.2	9.7	10.4	11.0
100	7.2	7.7	9.5	10.0	10.7	11.3

Table 12: Year 2050 Wave Height Distribution versus Recurrence Interval (Nantucket Airport Wind Data)

Recurrence Interval (years)	Stillwater Elevation (feet; NAVD88)	Total Water Elevation (feet; NAVD88)	Wave Crest Elevation (H_s; feet NAVD88)	Wave Crest Elevation ($H_{1/10}$; feet NAVD88)	Wave Crest Elevation ($H_{1/100}$; feet NAVD88)	Wave Crest Elevation (H_{max}; feet NAVD88)
Wave Distribution Exceedance Probability			13.5%	3.9%	0.4%	-
5	4.7	5.2	-	-	-	-
10	6.2	6.7	8.3	8.8	9.5	10.0
25	6.7	7.2	9.1	9.6	10.4	11.1
50	7.0	7.5	9.6	10.1	10.9	11.7
100	7.2	7.7	9.9	10.5	11.4	12.1

Table 13: Year 2050 Wave Height Distribution versus Recurrence Interval (ASCE 7-10 Wind Data)

Year 2070:

Recurrence Interval (years)	Stillwater Elevation (feet; NAVD88)	Total Water Elevation (feet; NAVD88)	Wave Crest Elevation (Hs; feet NAVD88)	Wave Crest Elevation ($H_{1/10}$; feet NAVD88)	Wave Crest Elevation ($H_{1/100}$; feet NAVD88)	Wave Crest Elevation (H_{max}; feet NAVD88)
Wave Distribution Exceedance Probability			13.5%	3.9%	0.4%	-
5	5.6	6.1	7.6	8.1	8.7	9.2
10	7.1	7.6	9.2	9.7	10.3	10.8
25	7.6	8.1	9.8	10.2	10.9	11.5
50	7.9	8.4	10.2	10.6	11.3	11.9
100	8.1	8.6	10.4	10.9	11.6	12.2

Table 14: Year 2070 Wave Height Distribution versus Recurrence Interval (Nantucket Airport Wind Data)

Recurrence Interval (years)	Stillwater Elevation (feet; NAVD88)	Total Water Elevation (feet; NAVD88)	Wave Crest Elevation (Hs; feet NAVD88)	Wave Crest Elevation ($H_{1/10}$; feet NAVD88)	Wave Crest Elevation ($H_{1/100}$; feet NAVD88)	Wave Crest Elevation (H_{max}; feet NAVD88)
Wave Distribution Exceedance Probability			13.5%	3.9%	0.4%	-
5	5.6	6.1	-	-	-	-
10	7.1	7.6	9.3	9.7	10.4	11.0
25	7.6	8.1	10.1	10.6	11.4	12.0
50	7.9	8.4	10.5	11.1	11.9	12.6
100	8.1	8.6	10.8	11.5	12.3	13.1

Table 15: Year 2070 Wave Height Distribution versus Recurrence Interval (ASCE 7-10 Wind Data)

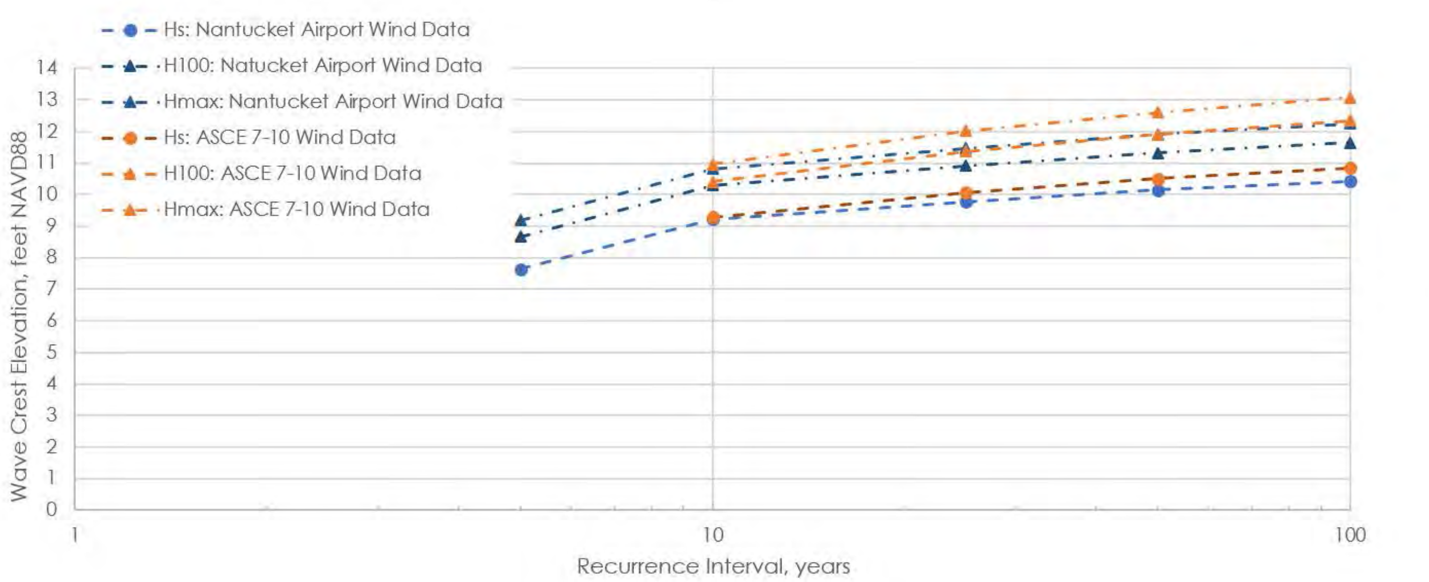

Figure 9: Year 2070 Predicted Wave Crest Elevation versus Recurrence Interval

Uncertainty

The values presented above represent mean values. Error and uncertainty around the mean exists for each of the hazard components (i.e., water level distributions, wave distributions and sea level rise). For simplicity, the mean values presented above are assumed a probability of 1.0.

Nantucket Airport Wind Speeds versus ASCE 7-10

As discussed in **Attachment 4**, two sources of wind data (Nantucket Airport and ASCE 7-10) have been considered and values are presented above for each of these. The principal difference between these data sets is the lack of intense hurricanes within the historical wind record for Nantucket Airport and the dominance of synthetic hurricanes in the development of the ASCE 7-10 winds. The Nantucket data also supports directional wind analysis. ASCE 7-10 is not directional. While it is reasonable to consider both data sets (and conservatively, ASCE 7-10), the likelihood of ASCE 7-10 hurricane winds aligned in a northeast direction is considered to be low (lower annual frequency than the applied all direction frequencies).

Based on engineering judgement and in recognition of the dominance of extratropical nor'easters to contribute the majority of risk (at least to the 50-year recurrence intervals), use of the Nantucket wind data is reasonable to this risk level. For lower annual exceedance probabilities (i.e., recurrence intervals greater than 50 years), it is likely that hurricanes contribute a more significant portion of the risk. As noted above, however, hurricane winds aligned in a northeast direction are likely lower probability than peak all-direction winds. Therefore, an assumption of ASCE 7-10 wind speeds in a northeast direction is expected to have a lower probability (recurrence interval greater than 100-years).

ATTACHMENT 9
Limitations

USE OF PLANS

1. GZA GeoEnvironmental, Inc. (GZA) has prepared construction plans on behalf of, and for the exclusive use of the Town of Nantucket ("Client") for the Evaluation of the Town Pier. Use of these study, in whole or in part, at other locations, or for other purposes, may lead to inappropriate conclusions; and we do not accept any responsibility for the consequences of such use(s). Further, reliance by any party not identified in GZA's contract for services (with the exception of purposes of regulatory review), for any use, without our prior written permission, shall be at that party's risk, and without any liability to GZA.

STANDARD OF CARE

2. GZA's services were performed using the degree of skill and care ordinarily exercised by qualified professionals performing the same type of services, at the same time, under similar conditions, at the same or a similar property. No warranty, expressed or implied, is made.

EXISTING CONDITIONS

3. The existing conditions described on the plans were made on the dates referenced. Conditions observed and reported by GZA reflect the conditions that existed at the time of our work. Such conditions are subject to change and conditions at the time of construction may differ from those shown on the plans.

COMPLIANCE WITH CODES AND REGULATIONS

4. GZA used reasonable care in identifying and interpreting applicable codes and regulations during project design. These codes and regulations are subject to various, and possibly contradictory, interpretations. Compliance with codes and regulations by other parties is beyond our control.

NUMERICAL MODELING

5. Numerical wave modeling was performed as part of this study. The Client shall be aware that numerical models provide, at best, an approximation of actual conditions and are subject to model error and other limitations. Results should be interpreted in consideration of these uncertainties and limitations.

PROBABILITY AND UNCERTAINTY

6. Waves, water levels, winds and sea level rise projections have been presented in terms of probability (annual exceedance probabilities). Values presented should be considered to be approximately "Best Estimate" values. The Client shall be aware that these values have uncertainty with upper and lower bound values.

GZA GeoEnvironmental, Inc.